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MEASURING LOSSES OF LEARNING DUE TO BREAKS IN PRODUCTION

by

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Measuring Losses of Learning Due to Breaks in Production

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ABSTRACT

The analysis of a break in production is usually performed by a government negotiator or cost analyst. The more effectively they are able to estimate the loss of learning due to breaks in production, the more likely that the final contract will be fair and reasonable. The research of this study focused on identifying the factors which contribute to a loss of learning due to a break in production and the methods which are available to quantify these factors. The four methods identified were the George Anderlohr, the DCAA, the Pinchon and Richardson, and the Cubic Curve. These methods were then analyzed using the data from two aircraft, the Grumman C-2A and the Bell Helicopter Textron AH-1W, both of which experienced breaks in production. This study concludes that the George Anderlohr approach is the most effective method to evaluate the loss of learning due to a break in production.

TABLE OF CONTENTS

I. INTRODUCTION

A. RESEARCH OBJECTIVE

The economic ramifications of determining the amount of lost learning during a production break can be very significant. Most often the review of a contractor´s proposal is left to either a Government negotiator or a cost analyst. The negotiator or cost analyst must first determine whether or not the contractor has used an effective method to evaluate the production break, and second determine whether or not another method, either quantitative or qualitative, will provide a better estimate of the loss of learning. The objective of this research paper is to identify the major factors which contribute to the loss of learning during breaks in production and to analyze current methods available to quantify these factors for a possible negotiation or cost analysis.

B. RESEARCH QUESTIONS

Given the preceding research objective, the following primary research question was posed: What are the principal factors which contribute to a loss of learning due to production breaks and how might these factors be quantified for use during negotiations?

The following subsidiary research questions were considered pertinent in addressing the primary question:

1. What methods have been and are used to measure loss of learning due to breaks in production?
2. What factors are affected by production breaks?
3. How can the effect on these factors be quantified and measured?
4. How best can negotiators use quantitative models of loss of learning due to production breaks in the buying process?

C. SCOPE OF THE THESIS

The thesis will focus on four current methods, found during a thorough review of literature, which identify factors which contribute to loss of learning or attempt to quantify the loss of learning during a production break. Three of the four methods emanate from the Government procurement system while the fourth is from the private sector. The thesis search for information was limited to those program managers, negotiators, and cost analysts, both Government and civilian, directly involved in the two cases used in this thesis, the Grumman C-2A and the Bell Helicopter Textron AH-1W. Specific information on these two cases was limited to proposals and estimated data which had taken place prior to contract award.

D. RESEARCH METHODOLOGY

Preliminary research for this thesis included a thorough examination of the literature base through the Defense

Logistics Studies Information Exchange (DLSIE) and the Defense Technical Information Center (DTIC) and review of numerous engineering and logistics journals and periodicals. In addition, all pertinent Department of Defense regulations and instructions were researched for applicable information.

Personal interviews were conducted, either by phone or in person, with Program Managers, Negotiators, and Cost Analysts who were directly involved with the two cases presented for analysis in this thesis. Additionally, cost analysts from the Naval Air Systems Command were interviewed for information concerning this thesis topic.

E. THESIS ORGANIZATION

The organization of this thesis is logically presented such that the reader can become familiar with learning curves and their theory before progressing into the methods with which to calculate the loss of learning due to breaks in production.

Chapter II of this thesis presents the history and theory of the learning curve. Since the learning curve forms the basis for evaluating breaks in production, a number of the specific examples are provided to more fully indoctrinate the reader.

Chapter III presents a detailed discussion of four methods the researcher identified to measure the loss of learning due to breaks in production. They are the George

Anderlohr Method, the DCAA Method, the Cubic Curve Method, and the Pinchon and Richardson Method.

Chapter IV presents a detailed analysis of the four methods to measure loss of learning due to breaks in production. This analysis is performed by utilizing the data from two aircraft, the Grumman C-2A and Bell Helicopter Textron AH-1W, both of which experienced breaks in production.

Chapter V contains the researcher´s findings, conclusions, and recommendations.

II. THE LEARNING CURVE

A. INTRODUCTION

The Learning Curve is based on two factors which occur when humans are involved in the production process. The first is that humans can learn and get more efficient or better at their job the more frequently they perform it. The second is that

> ...it was discovered that the direct labor input for each unit produced decreased with a predictable degree of regularity. More importantly, the amount of efficiency developed in direct labor through repetition of operations can be predicted over an entire production run. [Ref. 1:p. 44]

Since these facts will be used extensively in this paper, a brief history of Learning Curves will be presented followed by a detailed presentation concerning the theory of the learning curve. These include the unit cost curve, the cumulative average curve, and the S-curve. Additionally, the criticality of properly estimating both the slope of the learning curve and the first unit cost will be discussed.

B. HISTORY OF LEARNING CURVE THEORY

The origin of learning curve theory can be traced to a 1936 publication by T.P. Wright entitled, "Factors Affecting the Cost of Airplanes". His study showed that a relationship existed between average direct man-hour cost and the cumulative number of airframes produced [Ref. 2]. "He observed that on average when output doubled in the aircraft industry, the labor requirements decreased by about 20 percent, in other words, there was an 80 percent learning factor." [Ref. 3:p. 2] The enormous production of aircraft during World War II proved to be the perfect venue to test the theories of T.P. Wright. "The most influential of these was the Crawford-Strauss study which identified an average learning curve slope of 79.7% ("b"=-.32668) based on aggregate data for 118 World War II aircraft models." [Ref. 4:p. 9] As early as in 1946, the theories of T.P. Wright were being questioned. G.W. Carr published an article which questioned the very essence of Wright's theories. Whereas Wright's theory of learning curves for aircraft produced a linear (cumulative average cost curve) relationship, "...Carr hypothesized that the cumulative average cost curve would be "S" shaped when plotted on double log graph paper." [Ref. 5:p. 18] Carr's theory was based on three factors which occur during the production life cycle of a product. First is the incremental hiring of workers during production start-up or acceleration. The second factor is the amount of tooling and complexity of the assembly operations. The final factor which causes the flattening of the learning curve, occurs when current production techniques have reached a stable point and only changes to the production method will result in further learning or improvement.

The Boeing Airplane Company and the Stanford Research Institute also questioned the linearity of the cumulative average learning curve proposed by Wright. Boeing supported the theory of an initial concavity in the learning curve. They attributed this to careful planning and adequate tooling which will cause the cost per unit to drop significantly after production of the first unit. The Boeing research does support Carr's theory that eventually, the cost curve will level out due to tooling limitations. [Ref. 6:p. 13] Research done by the Stanford Institute again proposed a cost curve which was initially concave but unlike other theories, this curve did not eventually become flat. Instead, the "Stanford B Curve" produces a steeper curve as production increases.

The 1950's and 1960's led to further studies of learning curve theory. Specifically, many individuals studied the possibilities of applying Wright's original theory to the production within industries other than airplane airframes. Considered to be the initial breakthrough analysis, Mr. F.J. Andress published an article on this subject in 1954 titled, "The Learning Curve as a Production Tool". Mr Andress cited specific applications and examples for use of the learning curve theory in pricing labor hours during negotiations, in make or buy analysis and in production decision making. He also theorized that learning curves might be useful in such industries as Electronics, Home Appliances, Residential Home

Construction, Shipbuilding, and in machine shops. [Ref. 3] His article led to other studies which confirmed the applicability of the learning curve for use in such diverse industries as steel, petro-chemical, and electrical power. [Ref. 7] "Finally, learning was found to exist in process-oriented contexts as well as in job-order production, and in mature phases of production as well as in start-up." [Ref. 3:p. 2]

The work by the Boston Consulting Group (BCG),

> ...demonstrated that the learning curve effect encompassed not only labor costs [which had been the focus of much of the prior research] but also capital, marketing, and administrative costs. [Ref. 4:p. 10]

According to the BCG, all business costs followed a specific pattern, that unit costs decreased by one-third with each doubling of volume. The BCG used the term "Experience Curve" to delineate their applications from those of the original Learning Curve.

C. OTHER APPLICATIONS FOR THE LEARNING CURVE

More recent applications of Learning Curve Theory have focused on the following:

1. New Product Production Costs: Vance K. Wilkinson's 1980 study uses learning theory and the learning curve to predict production costs of products in transition from development to commercial applications. [Ref. 8]
2. Make or Buy Decisions: Use of learning curves can be used by a company to determine/estimate whether they

would be able to produce at less cost than their current suppliers.

> With some basic information concerning costs of subcontractors who propose to be the additional supplier, it might be determined how efficiently his labor is (or how far along the learning curve he is) in comparison with our own operations [Ref. 1:p. 46].

3. Suppliers Progress Payments:

> Since the learning curve reflects changing labor costs, it provides a basis for figuring a supplier´s financial commitment on any given number of units. [Ref. 9:p. 202]

A buyer can use learning curves to structure progress payments in relation to cost outlays by the supplier.

4. Analyze Pricing Practices of Suppliers: Figure 1 provides an example. During phase A of this graph the top producer is creating a price umbrella by increasing his price at a constant rate. This rise in prices may attract other producers. During phase B, the price of the product declines due to price wars among the producers. Phase C shows that the price war is over and a more competitive, stable market for this product now exists. Using the learning curve will help a buyer to be able to identify a suppliers pricing strategy and be able to plan a successful negotiation strategy. [Ref. 3] [Ref. 4]

5. Audit Evaluation:

> ...Today the improvement curve theory may be applied in the audit evaluation of costs and cost estimates in any industry, provided that the basic assumption of a relatively constant

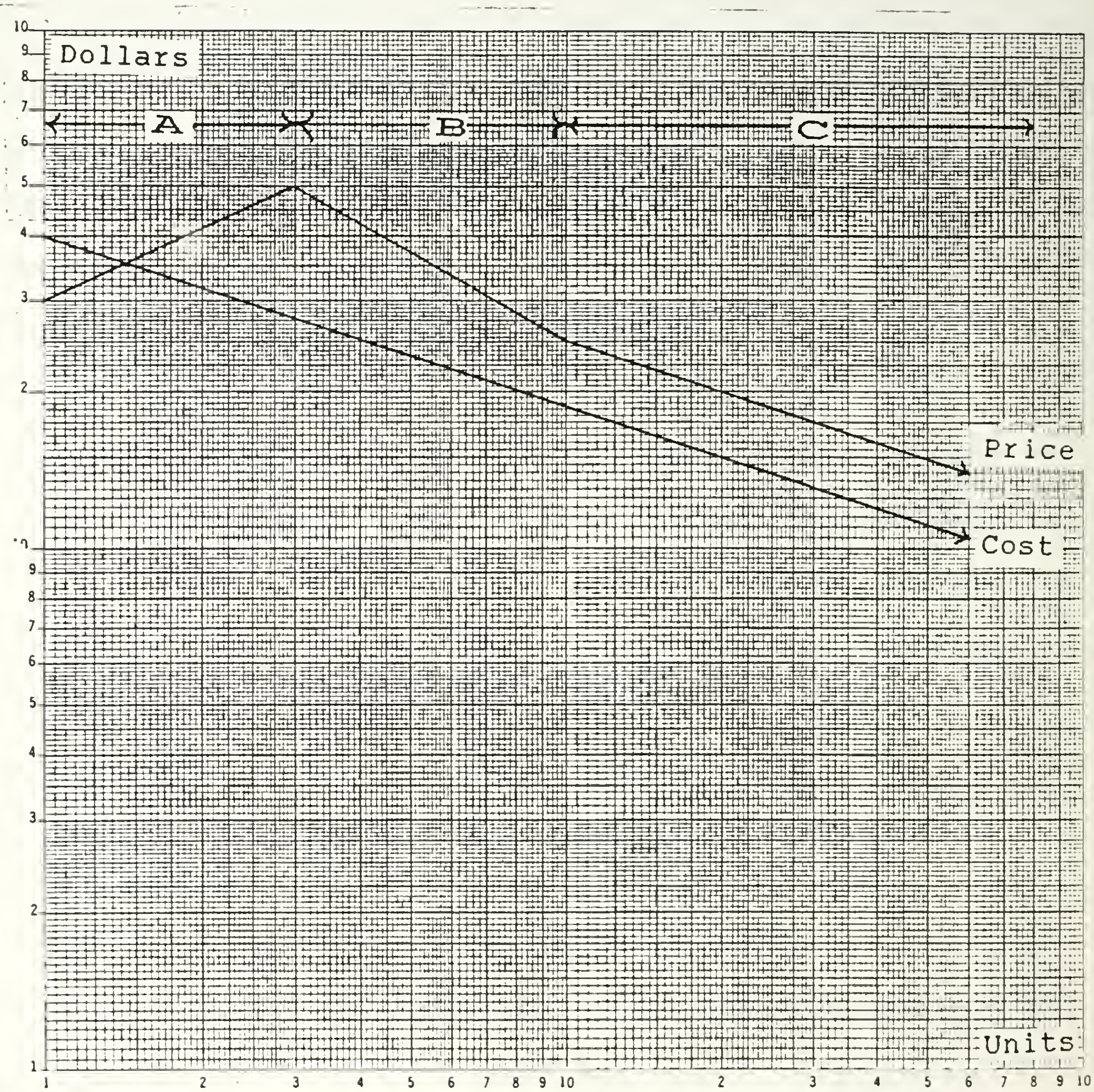

Figure 1 Pattern of Cost and Prices in Three Phases
Source: A. Belkaoui. The Learning Curve, 1986.

rate of improvement can be shown to be true for the particular cost-quantity relationship being studied. [Ref. 10:p. F-2]

6. Cost-Volume-Profit (CVP) Analysis: E.V. McIntyre has developed a model for using the learning curve factors in CVP analysis [Ref. 11].
7. Evaluation of Production Employees: Many studies have used learning curves to help evaluate the work of their production line employees. A manager would evaluate the individual workers learning curve against a model learning curve. Differences in the two curves would signal the manager that possible corrective action may be warranted. [Ref. 12] [Ref. 13]
8. Multi-year Procurement Analysis: Learning curves have been used repeatedly in the analysis of multi-year procurement. The analysis usually centers on the concept that stabilization of the learning curve for weapons systems, due to uninterrupted production resulting from multi-year funding, will cause overall costs to be reduced.
9. Production Rate Evaluation: Learning curves are used to analyze the effects of using varying production rates in major weapon systems acquisitions. The Rand Corporation and the Air Force have been particularly active in this field. Their research has focused on the development of parametric equations to show the

effect production rate changes have on direct labor hours or overall costs of a program. [Ref. 14] [Ref. 15] [Ref. 16]

D. LEARNING CURVE THEORY

The original theory, as formulated by T.P. Wright suggested the following relationship:

$$Y=aX^b$$

where Y is the average direct man-hours, X is the cumulated production of airframes, "a" is the man-hour cost of the first airframe, and "b" is the learning "elasticity" which defines the slope of the learning curve. [Ref. 17] Wright´s original studies estimated an 80% slope for the learning curve. Thus, as the quantity of airframes made doubles, say from 25 to 50, the labor cost declines by 80%, from 1000 unit man hours to 800 unit man hours. The preceding formula is the mathematical representation of the Learning Curve theory while Figures 2 and 3 show a graphical representation on linear graph paper and log-log paper.

The main use of the learning curve is in predicting the cost of future production. This is based on the assumption that historical production cost data will provide a clue or trend to future production cost data. Studies have proven this assumption to be fairly accurate when the plotted data approximates a straight line (when using log-log paper). The more the data points vary from the straight line the less accurate the data will be for approximation purposes.

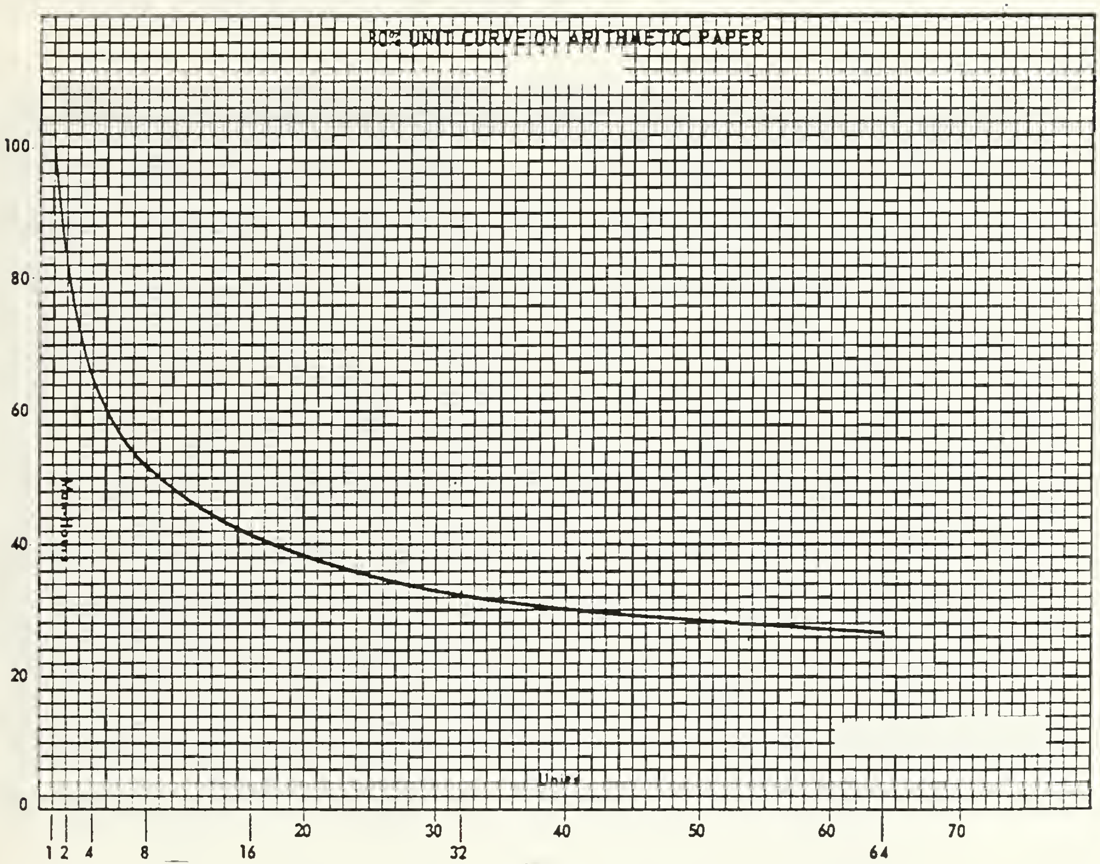

Figure 2 80% Curve on Linear Graph Paper
Source: Defense Contract Audit Manual, 1977.

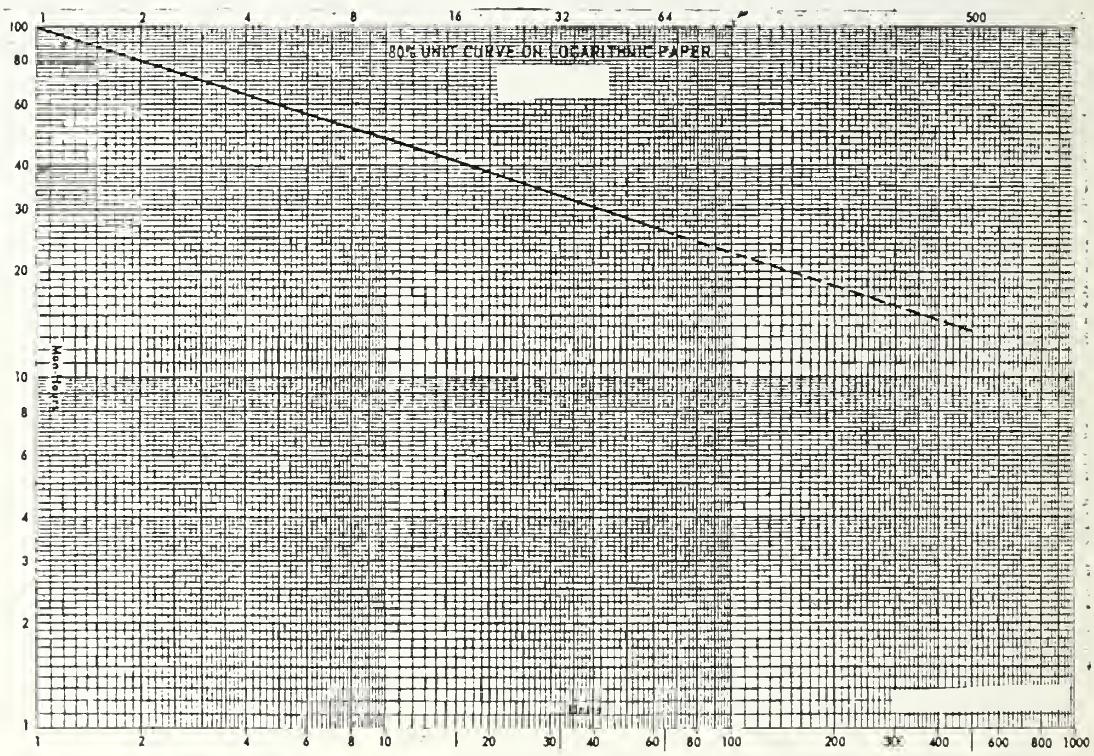

Figure 3 80% Curve on Logarithmic Paper
Source: Defense Contract Audit Manual, 1977.

The original T.P. Wright model has led to the development of two different theories for learning curve applications. They are the Cumulative Average Theory and the Unit Curve Theory. Each of these theories can be used with either a unit cost curve or a cumulative cost curve.

E. CUMULATIVE AVERAGE CURVE THEORY

This theory states that as the cumulative total units produced doubles, the cumulative average cost of each doubled quantity of production will decline by some constant factor or percentage. For instance, if we assume an 80% learning curve then the average cost of producing all of the first 500 units will be 80% of the average cost of producing the first 250 units. An example will prove beneficial in showing the difference in using a unit or a cumulative cost curve with this theory.

The data provided in Table 1 and the corresponding graph in Figure 4 highlight the differences between the two types of cost curves used with the cumulative average curve theory. Unit number 2 has a corresponding unit man-hours of 60 and cumulative average man-hours of 80. Unit number 4, a doubling in quantity from unit 2, shows unit man-hours of 45.37 and cumulative average man-hours of 64. The cumulative average man-hours exhibit the constant 80% reduction (80 X 80%= 64) expected using the cumulative average theory while the unit man-hours do not follow this pattern. The cumulative average cost curve in Figure 4 produces the linear

TABLE 1 80% CUMULATIVE AVERAGE CURVE THEORY
Source: Defense Contract Audit Manual, 1977

Unit No.	Unit Man-hours	Cumulative No. of Units	Cumulative Total Man-hours*	Cumulative Average Man-hours
1	100.00	1	100.00	100.00
2	60.00	2	160.00	80.00
3	50.63	3	210.63	70.21
4	45.37	4	256.00	64.00
5	41.82	5	297.82	59.56
6	39.19	6	337.01	56.17
7	37.13	7	374.14	53.45
8	35.46	8	409.60	51.20
16	28.06	16	655.36	40.96
32	22.33	32	1,048.58	32.77
64	17.82	64	1,677.70	26.21
100	15.42	100	2,270.62	22.71
1000	7.34	1000	10,819.71	10.82

* Totals include values of omitted units.

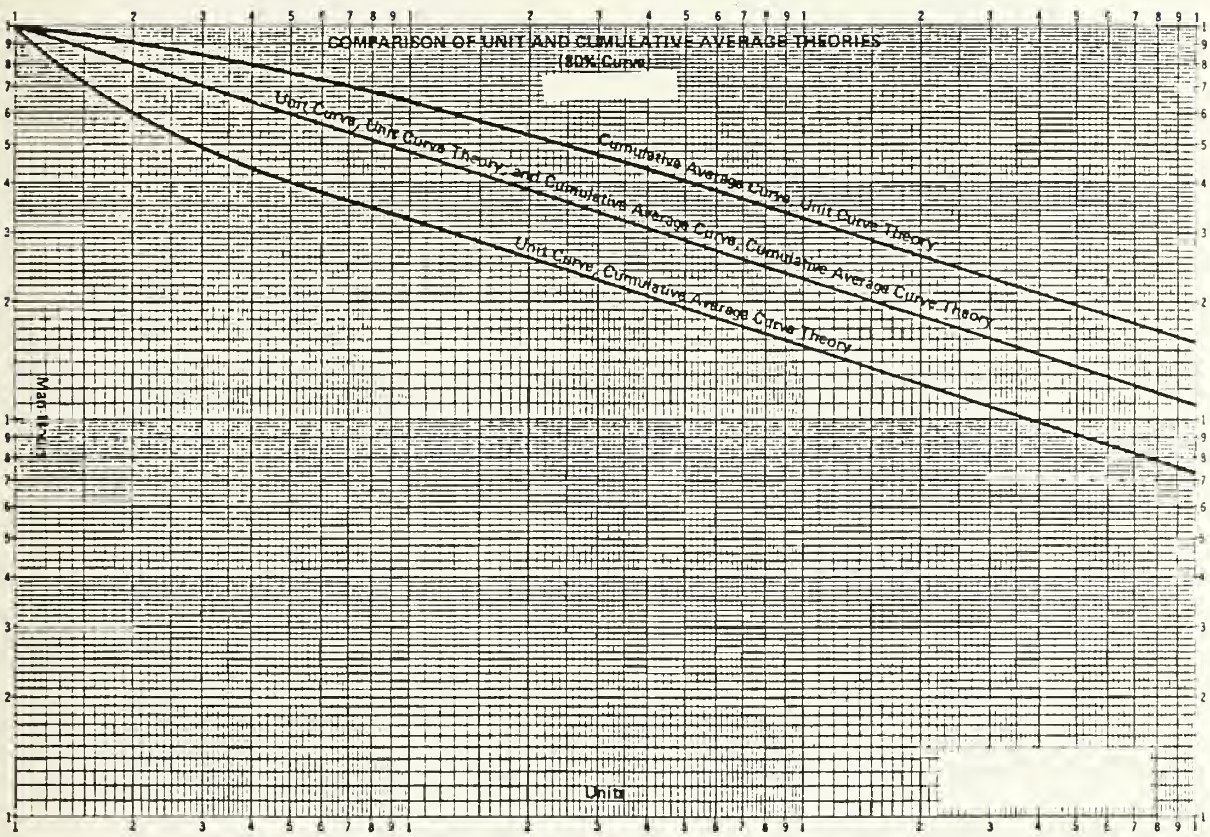

Figure 4 Unit and Cumulative Average Curve Theories
Source: Defense Contract Audit Manual, 1977.

learning curve as formulated by T.P. Wright. The unit cost curve, at low units of production, descends more rapidly than the cumulative average cost curve but as production continues the unit curve eventually becomes parallel to the cumulative curve.

F. UNIT CURVE THEORY

The unit curve theory is based on the theory

> ...that as the total quantity of units successively produced is doubled, the cost of each unit in a sequence of units based on doubled quantities (units 2, 4, 8, etc.) will decline by some constant percentage. [Ref. 10:p. F19]

The data in Table 2 shows the unit man-hours of labor in the second column and the cumulative average man-hours of labor in the fifth column. Note that when using the unit curve theory, the unit man-hours exhibit a constant 80% reduction for every doubling of quantity. For example, unit number two has a unit man-hour of 80 while unit four is 64. Comparatively, when cumulative average man-hours are used in the unit curve theory, unit two is 90 man-hours while unit four is 78.55 man-hours. The log-log graph in Figure 4 depicts the difference between the unit cost curve and the cumulative average cost curve when using the unit curve theory.

TABLE 2 80% UNIT CURVE THEORY
Source: Defense Contract Audit Manual, 1977.

Unit No.	Unit Man-hours	Cumulative No. of Units	Cumulative Total Man-hours*	Cumulative Average Man-hours
1	100.00	1	100.00	100.00
2	80.00	2	180.00	90.00
4	64.00	4	314.21	78.55
8	51.20	8	534.59	66.82
16	40.96	16	892.01	55.75
32	32.77	32	1,467.86	45.87
64	26.21	64	2,392.45	37.38
100	22.71	100	3,265.08	32.65
1000	10.82	1000	15,867.09	15.87

* The totals include values of omitted units.

G. COMPARISON OF UNIT CURVE AND CUMULATIVE AVERAGE CURVE THEORIES

The use of either the unit cost curve, with the unit cost theory or the cumulative average cost curve with the cumulative average theory will produce the same linear line for the same data. There are a number of factors which will influence which method should be used, either the unit cost or the cumulative average theory. They are:

1. Variations Within Data: The unit curve will show these variations while "...the cumulative average curve tends to smooth out aberrations to such an extent that even major changes can be obscured..." [Ref. 18:p. 114]
2. Availability of Information: Generally the military buys equipment in lots greater than one and thus receives cost data from contractors by lot and not on a unit basis. Research has shown that the majority of defense contracting is done using the unit curve theory with the cumulative average cost curve. [Ref. 19:p. 255]
3. Point in Production:

   > ...because of the lack of linearity in the first part of the curves, the use of the cumulative average curve for the unit curve theory and of the unit curve for the cumulative average curve theory is not practical for forecasting the early cost of production. [Ref. 10:p. F-25]

   Beyond early production, as can be seen in Figures 4, the unit curve or the cumulative average curves will produce linear curves and thus accurate forecasts when used with either the unit cost or the cumulative average theory.

The choice between these methods will depend on the data available. One should plot on log-log paper historical data available for evaluation using both methods. Of the resulting lines, the one which provides the best fit with respect to cumulative production should be used. To be more exact a computer regression analysis could be performed and the line with the lowest coefficient of determination would be used.

H. THE "S" CURVE

As noted in previous sections, the linear nature of the learning curve has been questioned by many theorists over the years [Ref. 20] [Ref. 21] [Ref. 22] [Ref. 23]. While the original theory of the "S" curve to describe what was felt to be the true shape of a learning curve when plotted on log-log paper is credited to G.W. Carr, two of the true leaders in this field of study have been Harold Asher in the 1950's and E.B. Cochran in the 1960's to the present. Mr Asher performed studies while working with the Rand Corporation and noted that "...the conventional linear progress curve is not an accurate description of the relationship between unit cost and cumulative output." [Ref. 24:p. 129]

Mr. Cochran has carried forward the study of factors contributing to the non linearity of the learning curve. Mr.

Cochran describes the factors which cause the initial plateau in the shape of the "S" curve as

> ...the need to debug new tooling and methods, shortages of parts and equipment as a result of design delays and changes, extensive rework and retrofit activities due to design changes and the difficulties met in developing a new production team. [Ref. 20:p. 417]

This portion of the "S" curve is identified by point A in Figure 5. Point B represents the portion of the "S" curve which is the same as would be found using the log linear concept of the learning curve. This portion of the curve will be influenced mainly by a company's

> ...reduction in errors, development of a rhythm or work pattern, rearrangement and changes in the workplace, changes in the distance moved, etc [Ref. 22:p. 40].

Section C of the "S" curve represents the point in the production cycle when learning has reached it's limit. The "S" curve begins to flatten out or in some instances, especially at the end of a production run/cycle, it may begin to "tailup". The "tailup" is due to many factors including:

1. transfer of experienced workers to other projects
2. increase in handwork as machines are disassembled
3. failure to replace or repair worn tooling at the normal rate
4. lack of adequate safety stocks to prevent shortages of key materials
5. workers taking more time to prolong the project and their employment

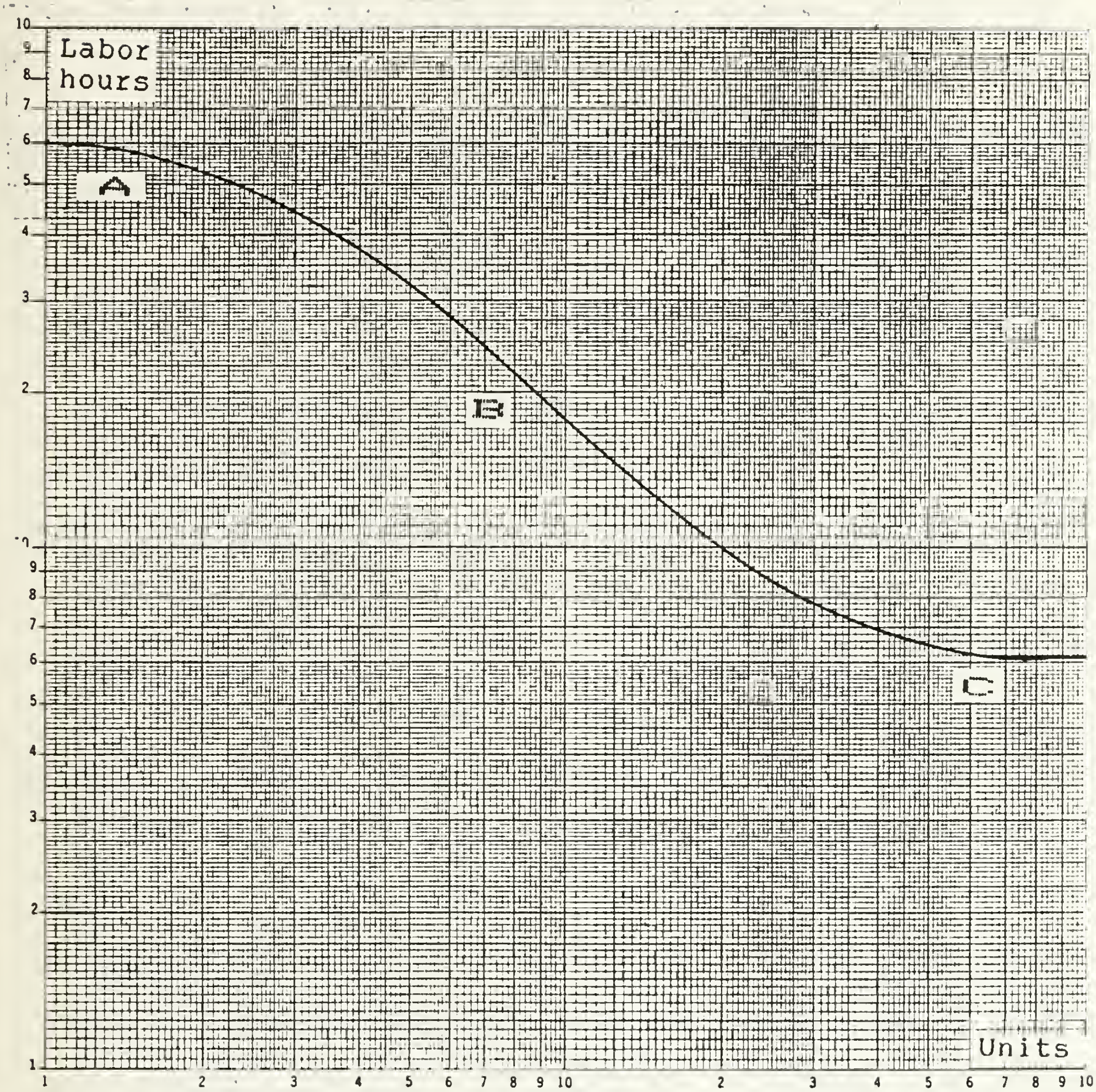

Figure 5 The "S" Curve
Source: Developed by researcher

6. less emphasis on the project by management personnel [Ref. 24]

Once again, as with the log linear curve, historical data should be analyzed before using the "S" curve. If the historical data for a company fits the general form of an "S" curve, when plotted on log-log paper, then this method may prove to be the most accurate method of measuring future costs.

I. THE SLOPE AND FIRST UNIT COST OF A LEARNING CURVE

Two factors should be analyzed very carefully when using the Learning Curve Theory to estimate production costs. They are both the suppliers estimated first unit cost and the slope of the learning curve.

1. The First Unit Cost of the Learning Curve

When looking at various estimated production learning curves as shown in Figure 6 the drastic differences in production costs by the 10th unit are evident. A comparison of curve A and curve B show the effect of the differences in estimate of the cost of the first unit of production. Curve A and curve B both have learning slopes of 80%. Curve A had a first unit of cost estimate of 500 hours/cost while curve B had a first unit cost of 400 hours/cost. Since these curves are parallel, curve A will always have a higher cost per unit at any given point of production. For example, at the 10th unit of production, curve A shows a unit cost of 240 hours, while curve B shows 195 hours. Likewise, at the 30th unit of

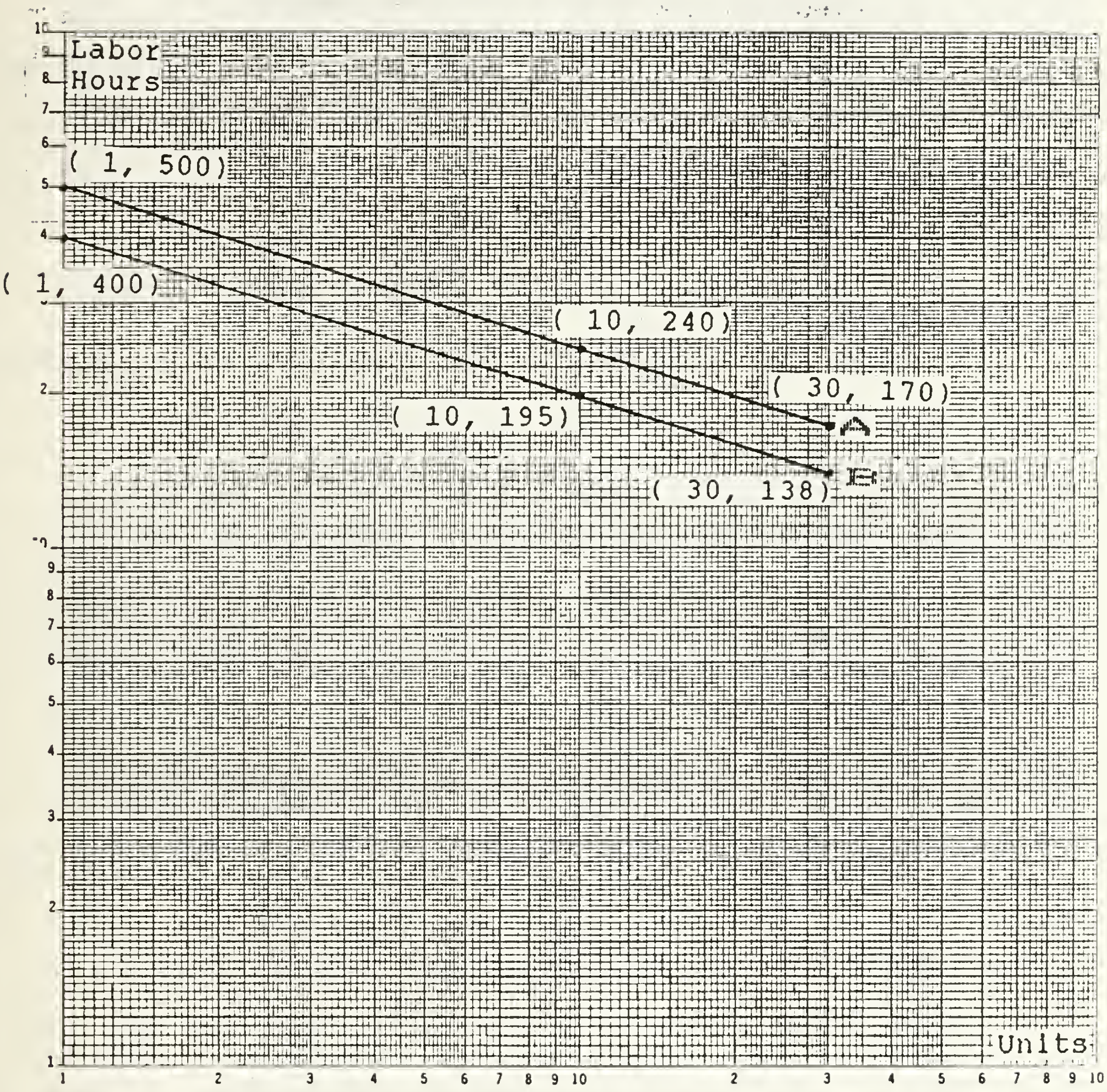

Figure 6 Comparison of First Unit Costs (Same Slope)
Source: Developed by researcher

production, curve A shows a unit cost of 170 hours and curve B shows 138 hours. One of the keys, during negotiations, for both the Government and the contractor, will be to try to establish a realistic first unit cost estimate.

This situation points out the necessity of carefully analyzing the estimate by a supplier for their first unit of production. The supplier's labor estimate must be carefully analyzed for the following possible miscalculations which could cause higher estimates of first unit costs:

1. inclusion of indirect labor hours as part of the direct labor hours for first unit of production
2. overestimating the labor mix of hourly low price workers with that of higher salary workers. Suppliers often tend to overestimate the labor hours of low rate hourly workers to drive up the initial cost estimates to reap benefits in the future.
3. initial engineering and tooling: "These are costs which are non-recurring and not subject to improvement curve phenomena..." [Ref. 26:p. 20]

2. The Slope of the Learning Curve

Curve A and curve C, in Figure 7, represent the cost ramifications of differently sloped learning curves. These curves have the same initial first unit cost with Curve A having an 80% slope and curve C having a 75% slope. With curve C having only a 5% better rate of learning than curve A (the lower the slope of the curve the higher the rate of

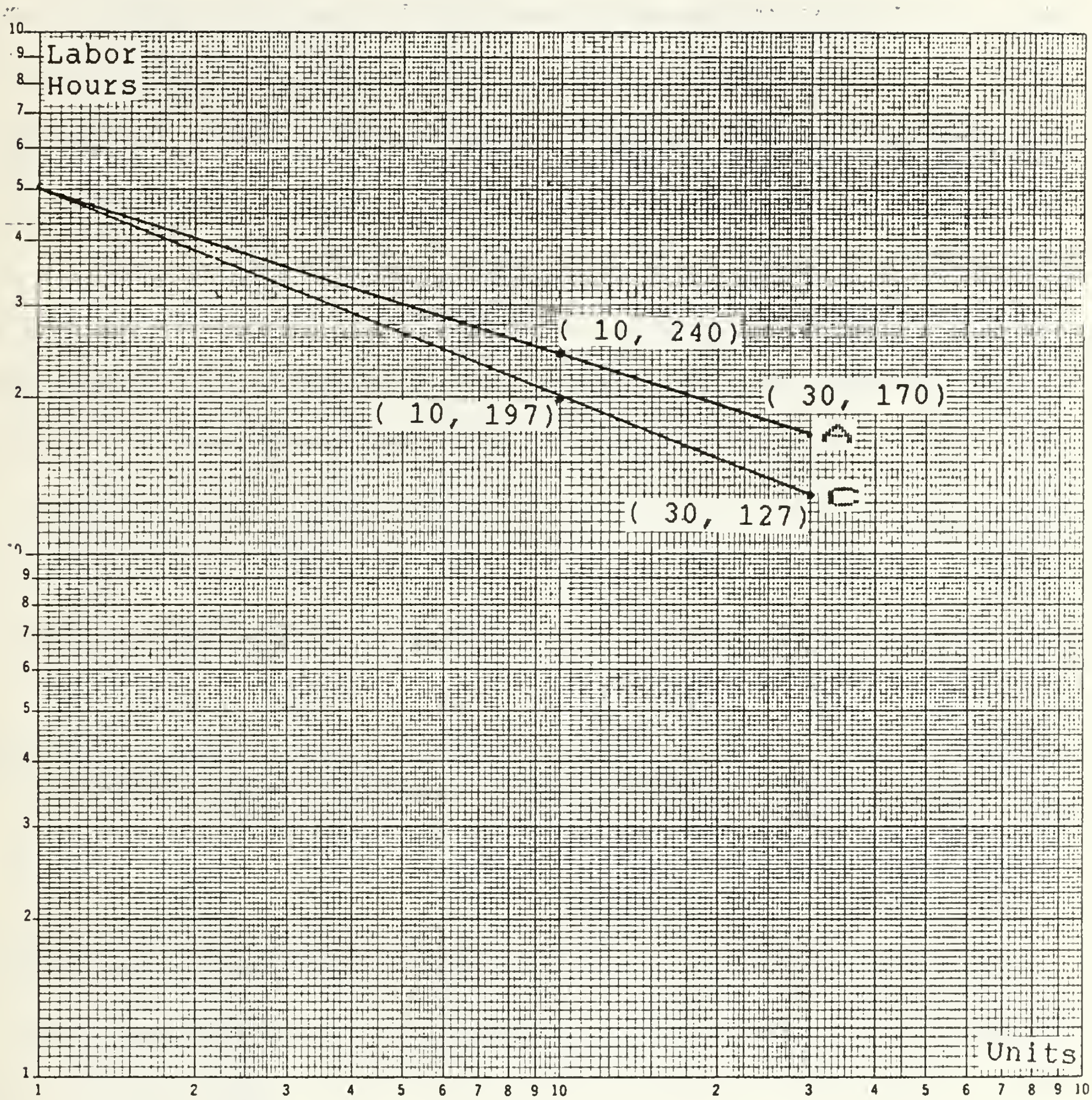

Figure 7 Comparison of Different Slopes (Same First Unit)
Source: Developed by researcher

learning), at the 10th unit produced, the average unit cost will be 197 hours while for curve A it will be 240 hours. When multiplying these estimated hours times the wage rates the 43 hour difference in the learning curves for the 10th unit estimation will be quite significant. These estimated hour costs for the 10th and 30th units were calculated graphically.

In general it can be shown that if there is an error in the estimate of the slope of a learning curve, assume 90% when it should have been 92%, there will be a 25% increase in total cost of the production of 1500 items. With an even steeper learning curve, an error in estimation could prove even more drastic. Using a 62% learning curve rather than a 60% learning curve will result in a 42% overstatement of total cost for the 1500 items and a 25% overstatement if 100 items are produced. [Ref. 25]

J. PRODUCTION LEARNING CURVES

Industrial engineers suggest that to properly evaluate a learning curve for a particular product it is necessary to look at a learning curve for the individual components which make up that product. Figure 8 shows the breakdown of the labor learning curve and the material learning curve, as well as the total learning curve for this product. By breaking down a product into component learning curves, industrial engineers hope to be able to isolate any specific factors causing less than expected cost reductions during production.

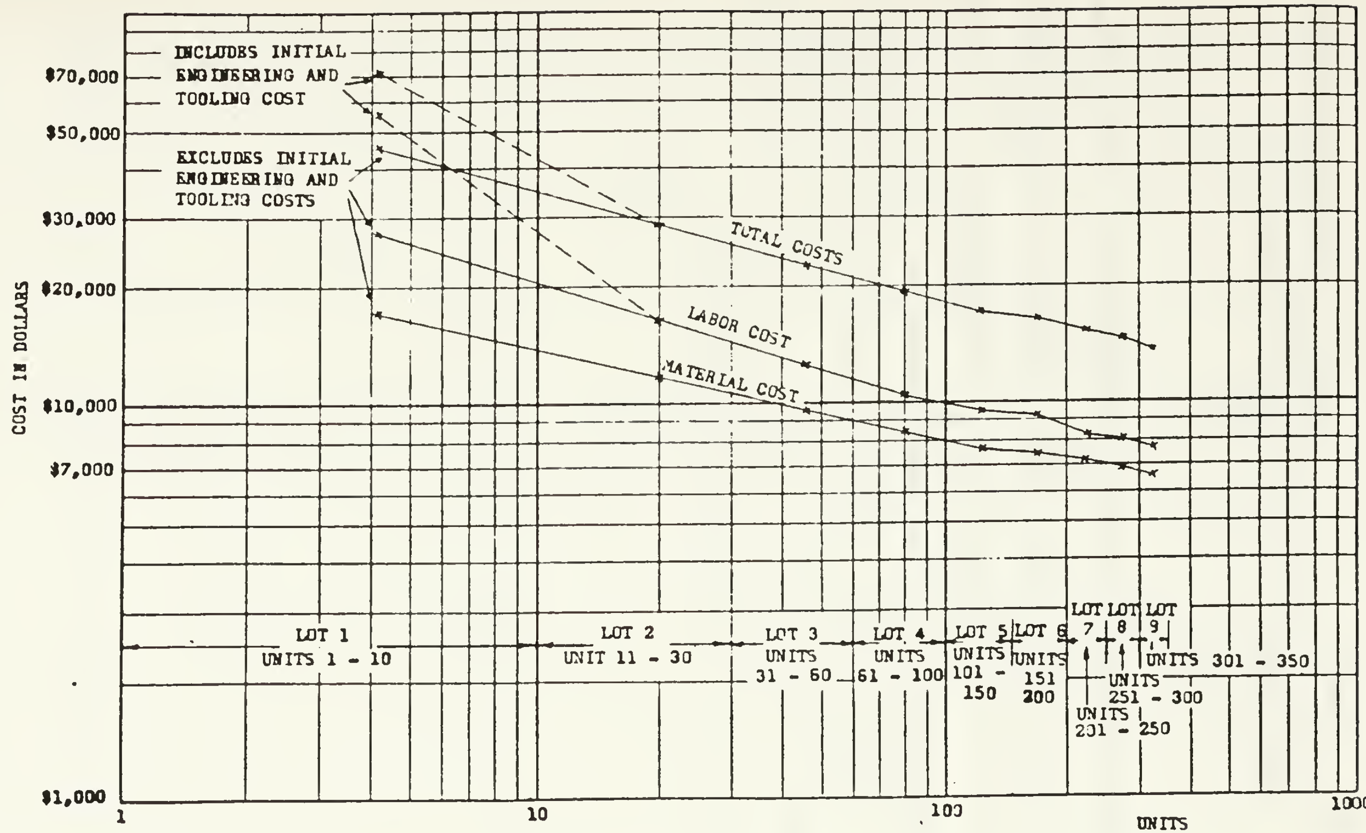

Figure 8 Individual Component Learning Curves
Source: W.K. Linnerooth. "Simplifying Improvement Curve Application", 1962.

Figure 9 provides another technique for breaking down the total cost of a product. This method shows the learning curves for sub-assembly, final-assembly, fabrication and the composite of these final cost centers. [Ref. 26]

K. SUMMARY

This chapter presented both the history of the Learning Curve and the theory of it´s use. The Unit Curve Theory and the Cumulative Average Theory were compared and contrasted. Finally, a discussion of the importance of the first unit cost and the slope of the learning curve was presented. These theories will be used in later chapters to quantify the loss of learning due to breaks in production.

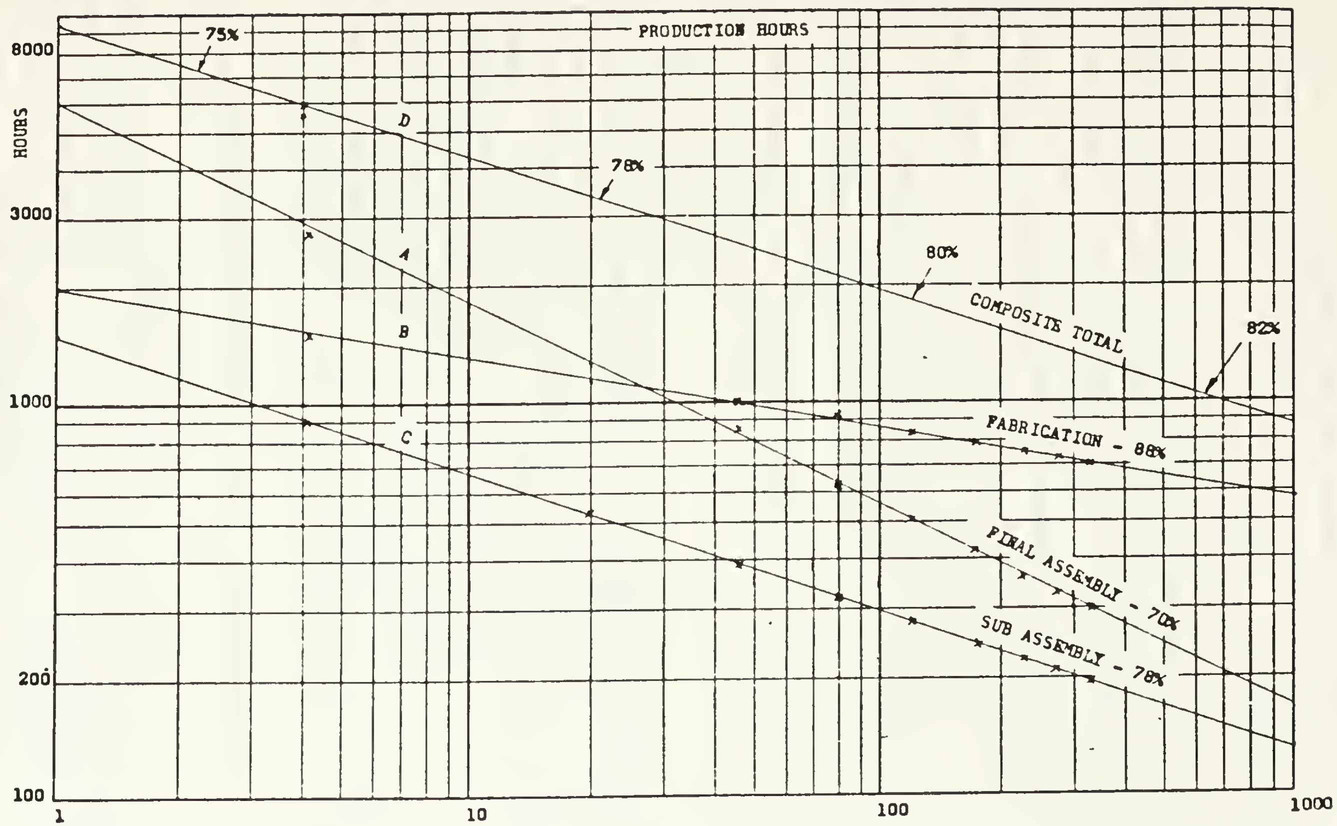

Figure 9 Elements of Total Cost Learning Curves
Source: W.K. Linnerooth. "Simplifying Improvement Curve Application", 1962.

III. BREAKS IN PRODUCTION

A. INTRODUCTION

One of the key assumptions for learning curve analysis is that production runs will be stable and no breaks in production will occur. However, contracting officers and negotiators must be prepared to do cost and labor hour estimations if a break in production should occur. [Ref. 2]

Mr. George Anderlohr, a former employee of the Defense Contract Administration Services (DCAS), defined a break in production as:

> ...the time lapse between the completion of a contractual requirement for the manufacturing of certain units of equipment and the commencement of a follow-on order for identical units of equipment. This time lapse disrupts the continuous flow of products. This could, in smaller shops, include a condition where the follow-on order was received prior to the delivery of the last units of the first order. An example of this would be the completion of circuit board assemblies, and all personnel had been moved into the final assembly area. Thus, the circuit board assembly line would have to be reestablished to accommodate the new order. [Ref. 27]

Anderlohr analyzed the problem with breaks in production and the use of learning curves as follows:

> A major problem with the application of the improvement (learning) curve has always been that it addresses itself to a perfect environment which rarely exists. A major condition for this perfect environment is an uninterrupted production cycle (one lot of identical units following another). When plotting actual labor hours on a curve, it has been long noted that any interruption in the orderly and continuous flow of work from one work station to another is accompanied by an increase of labor hours when production is resumed. This

has been commonly referred to as start up costs which relates directly to loss of improvement.

In the real world of government procurement there is, almost always, a break in the production cycle. There has been no established reliable method of compensating for the loss of improvement resulting from a break in production. General Electric Cost Accounting Service Bulletin No. PC-5 recommends a fifty percent loss of learning for a three to six month break and a seventy-five percent loss for a twelve month break. This is such a general approach that it would be extremely difficult to support in cost negotiations. Because of the lack of guidance, most cost analysts take almost arbitrary positions ranging from the use of unsupported percentages, as mentioned above, to the position that no learning was retained after a production break. The total loss of learning is usually based on a common misconception that learning or improvement is directly related to personnel know-how only.

Negotiators and Cost Analysts facing their counterparts across a negotiation table are frequently plagued with the recurring problem of estimating loss of improvement (learning). [Ref. 27]

Four different methods for calculating/estimating the loss of learning due to breaks in production will described in this chapter. The four methods are:

1. The George Anderlohr Method
2. The DCAA Method
3. The Cubic Learning Curve Method
4. The Pinchon-Richardson Model

B. THE GEORGE ANDERLOHR METHOD

The George Anderlohr method was originally published in a 1969 issue of Industrial Engineering. He identified five major elements or categories of company learning to evaluate for loss of learning. The five elements are:

1. **Personnel Learning** includes actually forgetting work procedures, hiring untrained replacement personnel and rehire of personnel.

2. **Supervisory Learning** refers to the loss resulting from transfer of supervisors, limited knowledge of new hires and the reduced guidance they furnish because of lost familiarity with the job.

3. **Continuity of Production** relates to the physical establishment of production lines, the position adjustments for optimal working conditions and work in progress build-up.

4. **Methods** concerns rerouting of operations due to in-plant changes since the last production lot.

5. **Special Tooling** describes short run versus long run tooling, replacement of modified tools and the effect of transition time. [Ref. 28:p. 19]

Totaling the calculated learning loss within each of these elements produces the overall loss of learning for the company. The final step in this method is to equate this company loss of learning to a specific point on the learning curve just prior to where the break in production occurred.

1. Example Using the Anderlohr Method

Mr. Anderlohr's method begins by applying a weighted average figure for loss of learning within each of the five elements of learning. Each element begins with a 20% baseline loss of learning standard. The 20% figure is then adjusted according to specific information available concerning the production break for that product. For category one, assume that information available suggests that only 75% of the suppliers trained production personnel are still available after a six month production break. Historical data indicate that these retained workers have lost 33% of their original individual experience during this break. Thus, the amount of retained learning for production personnel is calculated to be (20%) X (.75) X (.66)=9.9% and the learning lost is 20%-9.9%=10.1%. After similar calculations are performed within the four other categories, a final estimate of the company's percent of learning lost is obtained. In our example the cumulative total of the weighted average loss of learning is 50% from the five categories. This 50% figure is then multiplied by the "learning hours" for the first lot of production. Figure 10 provides a graphic depiction of this example. Prior to the production break, learning hours for Lot I are calculated as follows:

Unit 1=1000 hours
<u>Unit 20=381.5 hours</u>
First Lot Learning =618.5 hours

This first lot of learning is then multiplied by the 50% learning lost figure to yield a total production break learning loss of 309.2 hours. The next step is to add the calculated hours of lost learning, 309.2, to the 381.5 hours of the last unit made prior to the break, which produces the sum of 690.7 hours. This figure represents the predicted amount of hours needed for the first unit after the production break. Figure 10 shows how the second lot, post production break, has a starting point for further learning at unit 2.12 and the point on the learning curve 690.7 hours. [Ref. 29]

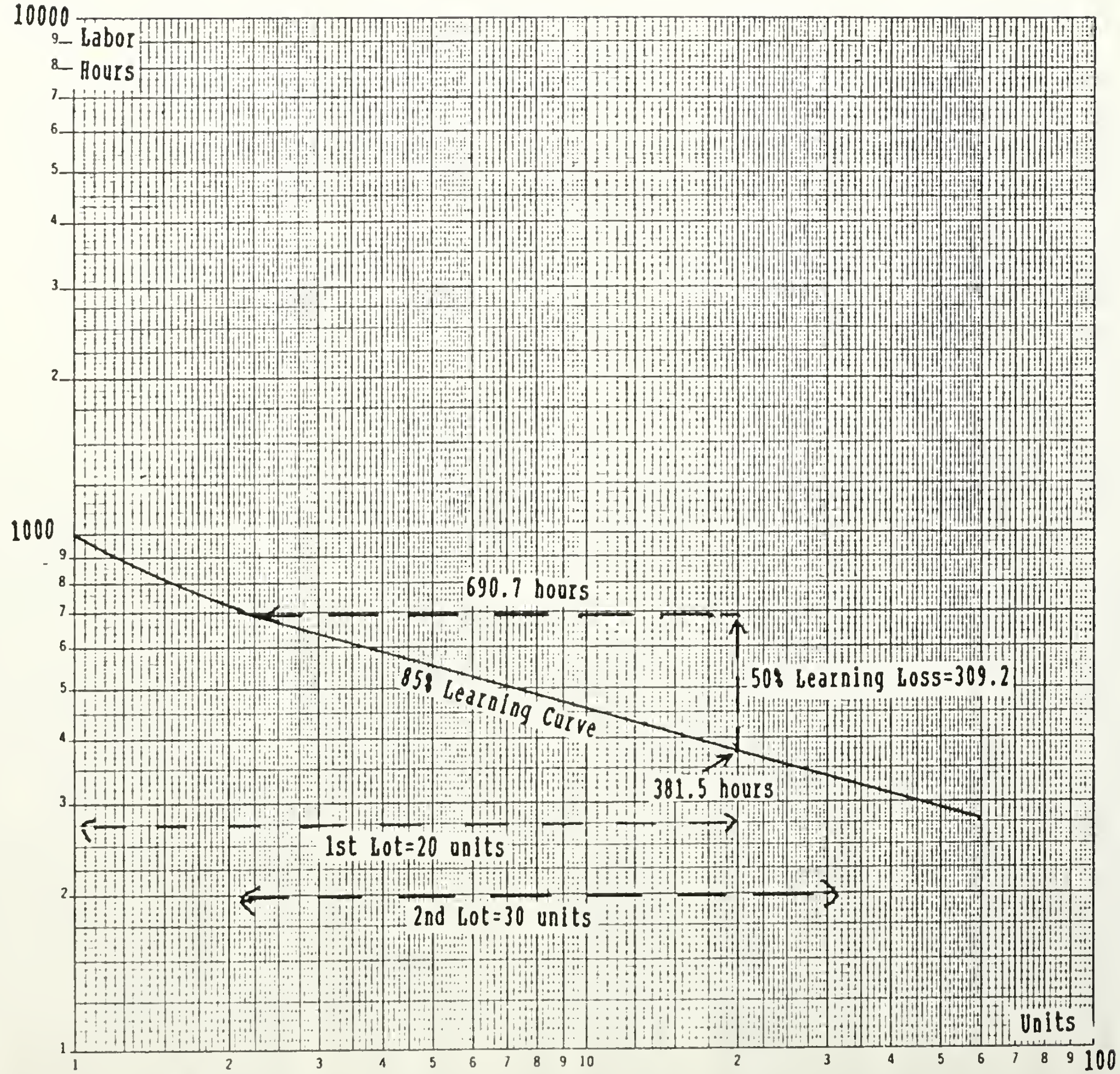

Figure 10 The George Anderlohr Method
Source: G. Anderlohr. "What Production Breaks Cost", 1969.

C. DCAA APPROACH

The DCAA method for calculating loss of learning due to breaks in production was developed as a result of a study done by Mr. Robert B. Ilderton. From his study

> ... a method was developed whereby a weighted least squares line is fitted, under the unit curve theory, to direct labor data before and after production break in efforts to determine how many units are lost due to a break in production [Ref. 30:p. 26].

The method developed, which is a modification of the basic learning curve equation, is as follows:

$$Y=K(X-AZ)^{c}$$

A= # units of learning lost because of break
Z= zero before break, 1 afterwards
Y= the number of Direct labor man hours required to produce the Xth unit
K= the number of Direct labor man hours required to produce the first unit
X= the unit number
C= log B/log 2 where B equals learning curve factor (.90, .85, .70, .75...)

The first step in using this method is to determine the value of the learning curve, C, from the historic data which took place before the break. This can be done by either visually drawing a line through the data after plotting it on log-log paper or, by using computer linear regression techniques. The first unit cost or K value in the model can also be determined using one or the other of these methods. After calculating the K value and the C value, the next step is to determine the value to use for parameter A, the number of units of learning lost because of the break in production. This is done by imputing successively larger values for A

(0,1,2,3...) into the model equation, while using the successive unit numbers (X values) for the new lot of production. The resulting data will be a predicted Y value, in unit hours, for each unit number entered (X value). A least squares fit for the X values and Y values is performed to obtain a corresponding R^2, index of determination. If the R^2 value for A=0 is greater than the R^2 value for A=1, then the least squares best fit for the data has been obtained and the new lot values should be calculated using A=0. If the R^2 value for A=1 is greater than for A=0 the procedure must continue until a point where the R^2 values stop increasing and start decreasing from the prior unit. [Ref. 2] This A value, which produces the highest R^2, will be used along with the first unit number after the break, in the model formula to calculate the first unit cost after the break.

D. CUBIC LEARNING CURVE

As noted in the previous chapter, many learning curve theorists have questioned the appropriateness of using the classic learning curve, $Y=KX^n$, which produces a linear learning curve. Many feel that the "S" shaped curve is a more accurate representation of the trend of labor costs when confronted with an irregularity in the production cycle. E. B. Cochran has identified an analytical framework which presents 16 contributing factors which can effect six major irregularities in the learning curve. Figure 11 presents

Contributing Factor	Major Irregularity Produced					
	A Startup	B_1 Accel-eration	B_2 Decel-eration	C Task Change	D Inter-ruption	E Phaseout
1. Degree of man-pacing (production slope)				X	X	X
2. Position on unit sequence				X	X	
3. Production Rate	X	X	X		X	X
4. Basic personnel efficiency and on-the-job training time	X	X		X	X	
5. Debugging of tools/methods	X			X	X	
6. Support services: supervision, materials, equipment, etc.	X	X		X	X	
7. Delays: tools, design, personnel, materials, etc.	X	X		X	X	
8. Task Changes						
o Progress: task reduction	X			X		X
o Configuration Changes	X			X		
9. Personnel: turnover, morale			X		X	X
10. Rate of learning: no. of crews, shifts, lines; parts used/unit	X	X	X			X
11. Task re-assignment				X	X	X
12. Work force increases	X	X				
13. Work force reductions			X			X
14. Lot size changes	X	X	X			X
15. Loss of learning				X	X	
16. Rework and retrofit	X			X		X
	11	7	5	11	10	9

Figure 11 Contributing Factors in Major Irregularities
Source: E.B. Cochran. "A Generalized Approach to the Improvement Curve", 1980.

this model. Notice that an interruption in production/production break is affected by ten of the listed contributing factors. All of these factors must be analyzed to determine the overall effect caused by a break in production. Mr. Cochran comes to the conclusion that

> The period leading up to a suspension of operations may involve all the complexities of a full-blown product phaseout. Depending on how long production is suspended and the design and methods changes injected upon resumption, we may then have something like a new product introduction with all the problems of acquiring and training personnel, refurbishing tooling, starting up, and developing a going operation; often at a lower production rate than before. [Ref. 20:p. 4-20]

Use of an "S" shaped curve is recommended by Cochran to predict the start-up of a new item in production or an item which has been subjected to any of the six major irregularities noted in Figure 11 [Ref. 20].

In their paper titled, "How Much Does Forgetting Cost", John G. Carlson and Alan J. Rowe also support the use of cubic curves ("S" shaped on log-log graph paper) to analyze the loss of learning due to interruptions in production [Ref. 31].

The method for the cubic curve from which Carlson and Rowe developed their analysis was originally published in an article written by Frank D. Miller of the IBM company. Mr. Miller noted that an "S" shaped curve on log-log graph paper could best be represented by a third-order polynomial. The equation for the cubic learning curve is:

$$Y= AX^3 + BX^2 + CX + D$$

When solved, the four coefficients, A, B, C, and D will determine the shape of the cubic curve. To solve for these coefficients the following information is needed:

1. The point (X_o, Y_o) which represents unit number one and the labor hours to produce it.
2. The slope/derivative at the first unit, dy/dx_o.
3. The Point (X_n, Y_n) which represents the unit and the cost of producing the last unit.
4. The slope/derivative as it approaches the last unit, dy/dx_n.

The four coefficients can be calculated by entering the two points and slopes into the following four equations and subsequently into a matrix and performing matrix inversion and multiplication operations:

$$AX_o^3 + BX_o^2 + CX_o + D = Y_o$$

$$AX_n^3 + BX_n^2 + CX_n + D = Y_n$$

$$3AX_o^2 + 2BX_o + C = dy/dx_o$$

$$3AX_n^2 + 2BX_n + C = dy/dx_n$$

Once these coefficients have been determined, by entering the number of a particular unit X into the cubic equation, the cost, in hours, of producing that unit, Y, can be determined. Thus, with an estimate of the first unit cost, the last unit cost, and the learning curve values at those points, it is now possible to estimate the total cost of a follow-on lot after a break in production. [Ref. 21]

E. THE PINCHON AND RICHARDSON METHOD (PR)

This model was developed by two Air Force Captains as their thesis study which, "...resulted in a mathematical model for predicting the first unit cost following a break in production by use of step-wise regression techniques" [Ref. 27].

The general model which they developed from their study was as follows:

$$\ln Y = A_o + A_1 \quad X_1 + A_2 \ (\ln X_2)$$

Y = The calculated independent variable (1st unit cost after production)
A_o = regression constant
A_1 = regression coefficient for X_1
A_2 = regression coefficient for X_2
X_1 = learning curve factor
X_2 = last unit direct labor hours for the lot(s)

Pinchon and Richardson then used sample data from production breaks which occurred in small machine shops to develop a specific equation. The average labor hours per unit produced was less than ten. The specific equation which they then calculated was:

$$\ln Y = 1.09948 + .0602 \ X_1 - 7.9545 \ (\ln X_2)$$

To use this model, the X_2 value or the slope of the learning curve and the X_1 value, the unit direct labor hours for the last unit produced prior to the break in production must be determined. These values can be calculated by applying a least squares regression analysis to the lot produced prior to the break. To use the specific equation developed by P&R, the following criteria must be met:

1. All learning prior to the production break must be considered lost.
2. Items must require less than 50 hours for production, if not then new values for A_0, A_1, and A_2 must be calculated.

If these criteria can be met then the first unit cost can be calculated by entering the value of X_1 and X_2 into the specific equation. The Y value which the equation will yield is the first unit cost after the break in production.

F. SUMMARY

In this chapter the nature of a break in production and it´s relationship with learning curves was identified and discussed. Four different methods, the George Anderlohr method, the DCAA method, the Cubic Learning Curve method, and the Pinchon and Richardson method have been presented for use when quantifying the loss of learning due to breaks in production.

IV. ANALYSIS OF TWO AIRCRAFT

A. INTRODUCTION

This chapter will examine two aircraft, the Grumman C-2A and the Bell Helicopter Textron (BHT) AH-1W, "Sea Cobra", which experienced breaks in production prior to their most recent procurement. The four methods introduced in Chapter III for determining the loss of learning due to breaks in production will be evaluated based on their strengths and weaknesses using the data, in the Appendix, for these two aircraft. Additionally, the principal factors which effect loss of learning for these four methods will be presented.

B. GRUMMAN C-2A

The C-2A is used by the Navy as a cargo aircraft to deliver equipment, supplies and personnel to aircraft carriers. Grumman is the sole source for production of this aircraft. The original production quantity was 19 aircraft, of which two were developmental, four were in Lot I, eight were in Lot II, and five were in Lot III. The last of these aircraft were delivered in 1967. The new procurement, for 39 aircraft, was scheduled for delivery beginning in 1985. Thus, there was a 17 year break in production for this aircraft. It should be noted however, that the E2-C, which has the same wings, power plant, and tail configuration, were being produced during this 17 year production break of the C-2A.

The method used by Grumman to estimate the loss of learning due to this 17 year production break was divided into three parts. They were:

1. C-2A Peculiar: This was the estimation of direct labor hours required to produce the fuselage of the C-2A. Grumman's calculations proposed a 2/3 setback on the old C-2A procurement learning curve. These calculations were based on a four and one-half year break in production which occurred between C-2A unit 19 (cumulative E2-A, C-2A unit 76), and the first unit built for the E2-C (cumulative unit 77). Grumman determined the theoretical hours for unit one after the break based on a regression analysis of five consecutive lots, which were produced after the break. The theoretical value for unit one of the E-2C, after the break, was then equated to a value from a unit produced prior to the break, unit 26 of cumulative production. This leads to the calculation of the 2/3 setback as follows:

   (77-26)/77 = 66 2/3 % Loss of Learning

   Additionally, Grumman projected the first 14 re-procured aircraft on a 71% learning curve slope and the last 25 aircraft on a 80% slope due to similar circumstances which took place for the first three lots of C-2A production. Thus, the 66 2/3% loss of learning estimate was based on one historical break in production and the ratio between the hours of a first unit after a break, calculated using regression analysis, with an equal unit, in hours, which occurred prior to the break. The 2/3 setback causes the loss of learning to be quantified in the difference between the regression calculated last unit produced prior to the break of 80,626 versus the estimate of the first unit after the break taking 135,000 peculiar hours.

2. C-2A Common: This was the estimation of direct labor hours required to produce common components between the C-2A and the E-2C. The estimate was based on actual ongoing production from the E2-C. Concurrent production of the E-2C and the C-2A was expected to lower the overall learning curve slope for these components.

3. New Delta Tasks: New improvements required for the proposed C-2A production which were not required for the original production lots was estimated based on the new design engineering plans. Seven percent of total labor hours was the estimate for new delta task hours.

The Government´s contentions with Grumman´s estimating technique focused on the estimate of the first unit hours after the four and one-half year break and the various learning curve slopes which were proposed. However, after some correction of data and changes in the contractor's make or buy plan, the original method proposed by Grumman for determining the loss of learning, resulting in a 2/3 setback, was accepted during negotiations. The final contract agreed to was a fixed price incentive contract with a 50/50 share ratio above and below the target price.

C. BELL HELICOPTER TEXTRON (BHT) AH-1W

The AH-1W is a light/attack helicopter which is procured on a sole source basis from BHT for the United States Marine Corps. As of 1984, more than 1800 AH-1's had been built progressing from the AH-1G to AH-1J to AH-1Q to AH-1S to AH-1T and finally the AH-1W. Principal buyers were the United States Army, the United States Marine Corps, and several foreign allies. [Ref. 32:pp. 135-136] The proposed contract for the procurement of 34 planes, Lot III, was to be the final buy of this type aircraft by any of the Services. Lot II was completed approximately 40 months before Lot III was anticipated to begin. During this break in production, BHT was performing a block upgrade of 21 AH-1T's into AH-1W's.

The method used by BHT to calculate the loss of learning was based on past experience in the AH-1 program, in which four other breaks in production took place. The steps involved in evaluating the four historic breaks were as follows:

1. Determine the line of best fit, using regression analysis, for data prior to the break in production.

Using this best fit learning curve calculate the labor hours for the last unit produced prior to the break.

2. Determine the line of best fit, using regression analysis, for data which occurred after the break in production. Using this best fit learning curve, calculate the first unit cost after the break.
3. Develop a growth factor by taking the ratio of the first unit cost after the break to the last unit cost before the break.
4. Using the growth factors from each of the four breaks, as the independent variable and the respective length of each break as the dependent variable, perform a line of best fit regression analysis for this data.

Using the resulting linear equation, given the length of a break in production, an estimated growth factor can be calculated. This growth factor will allow an analyst to estimate the first unit cost after a break by multiplying the last unit labor hours before a break times the growth rate. Using the last unit hours, prior to the break in production, 6129, and the growth factors, Airport (2.957), Final Assembly (3.054), and Major Components (2.867), the estimate for the first unit after the 40 month break will be 17,820 hours.

D. GEORGE ANDERLOHR METHOD

The specific data to perform an in depth analysis of the C-2A and the AH-1W, using the George Anderlohr method, was not available. Normally a negotiator or cost analyst would gather a significant portion of the information necessary to use this method during a fact finding visit to the contractor´s plant. Instead of performing the specific calculations for this method, a discussion/analysis will be performed using the five elements of company learning suggested by Anderlohr, with respect to the C-2A and AH-1W. Discussions with Mr. James C. Eckert (Contracts Manager), Dick Verderber (Negotiator), and Harvey Frommer (Program Manager) from Grumman, and Mike Walsh (Assistant NAVAIR Program Manager AH-1W), and Bill Wilson (Manager Government Contracts, BHT) form the background for this analysis.

1. C-2A

For the C-2A proposal, Grumman divided their labor hours into three parts: peculiar, common and new delta. Since the common hours between the C-2A and the E-2C were based on concurrent production of these aircraft there is no loss of learning calculation necessary. To calculate their new delta a straight percentage of overall labor hours was used so again no learning loss was indicated. Therefore, the analysis using the Anderlohr method will focus on the peculiar hours estimation for the C-2A.

a. Personnel Learning

Since this element specifically concerns the loss of personnel, for Grumman, after a 17 year break, there were few workers left from the original lots of production. Those who may have been left were working on the E-2C production line. Since production of the E-2C was to continue during the new production of the C-2A, it can be assumed that new inexperienced workers will have to be hired for the C-2A production line. A review of the tasks to be accomplished by these workers, with respect to the complexity of their jobs, would be required. The analyst needs to determine what percentage of the workers' jobs are to be filled with journeymen, requiring no formal training, as opposed to specialist tasks where detailed training would be necessary. If it turned out that it was a 50/50 split, then the conclusion would have been that a 50% loss of learning was experienced for personnel. The analyst/negotiator should also review jobs to determine if any have been mechanized or are now being done by robotics. When machinery or robotics are being used, little loss of learning should be expected. For Grumman the production line was to operate in the same manner as it did 17 years ago, predominantly in a manual mode.

b. Supervisory Learning

An analyst using the Anderlohr method should review Grumman's plans for acquiring key management personnel to supervise the C-2A project. If supervisors were being brought over from the E-2C project, then only a partial loss of learning would be expected in this element. If all new supervisors had to be hired, then a significant loss of learning would be expected.

c. **Continuity of Productivity**

Two factors seem most important when analyzing this element. First, the old production line has been shut down for over 17 years. Thus, it would be un-realistic to assume that the synergy of an effective, efficient production operation will be possible until the new production operations have been on line for a period of time. Second, since this is a one time buy of this aircraft, inventories of parts and supplies will be kept to a minimum by the contractor increasing the likelihood of stock outages. These, in turn, would cause further disruptions in the continuity of production.

d. **Methods**

The method sheets or production plans, even after a 17 year break, should still be available to Grumman. An analyst will have to determine the changes required to these plans and instructions due to manufacturing techniques currently being used within Grumman's facilities.

e. **Special Tooling**

A check of the old equipment used during the first production run should be made during a fact finding visit. An analyst should verify the equipment which will require repair, overhaul, and or replacement. These facts will help determine the amount of learning loss in this element.

f. Summary

In assigning the weighted percentage for the five individual elements, an analyst/negotiator must decide the importance of the element to the overall production operations. In the case of the C-2A, which is a very labor intensive production operation, the personnel learning and the supervisory learning should be given a higher weighted percentage. In this case possibly 30% for each. This would leave the other 40% to be divided between the other three less important elements.

Once the calculations within these five elements are made and a total loss of learning percentage is calculated, the next step is to perform the setback as shown in Figure 10. Using the theory espoused by Anderlohr, the learning curve to be used will be the same for both the pre-break and the post-break production lots. However, after a break of almost 17 years, it is highly unlikely that the learning curve slope will be the same. Instead, the negotiator should review other current programs within the company, such as when Grumman used the E-2C program, to determine a fair and reasonable learning curve slope.

2. AH-1W

The circumstances of the AH-1W break in production are quite dissimilar from those of the C-2A. Even so, the Anderlohr methodology is still pertinent. Again this analysis will be done by reviewing the loss of learning within the five elements of company learning.

a. Personnel Learning

Discussions indicated that there was very little loss of personnel during the break between Lot II and Lot III. BHT was able to shift their workers to other areas of the company. Additionally, the modification of the 21 AH-1T´s into AH-1W´s began during the break and workers could be used to perform this operation. Thus, only minor loss of learning should be projected in this element.

b. Supervisory Learning

This category would be evaluated in the same manner as for personnel learning and result in only a minor loss of learning. BHT should provide specific documentation to prove that there has been significant turnover in supervisory personnel.

c. Continuity of Production

The production line for the AH-1W´s was shut down during the 40 month break. Therefore, there will be a significant loss of effectiveness when the line is re-assembled. The primary loss of learning will be from workers on the line having to get re-adjusted to working with each other. Workers, who have been employed on other production lines, will have to re-acquaint themselves with working on the AH-1W after having been working on the AH-1S.

d. **Methods**

There should be little or no effect from the break in production in this element. The methods will be virtually the same for the production of Lot III of the AH-1W as they were for Lot II.

e. **Special Tooling**

The equipment which formed the production line for Lot II was taken apart and put into storage during the break. This equipment will have to be fixed and put back on line before production can restart. During the fact finding visit, the negotiator/cost analyst can investigate the equipment to determine the extent of wear, breakage, or missing equipment. A consideration in this area is the fact that since this is the final planned buy of AH-1W's by the U.S. Government, the contractor will be less likely to invest in new equipment, instead preferring to repair the old equipment. The use of less than optimal equipment may have a negative effect on learning.

f. **Summary**

Summing the loss of learning estimates within each of these elements will yield an overall learning loss for the company. The analysis of the five elements of company learning would indicate that BHT should not have a significant loss of learning. There does not appear to be any single area, with the possible exception of tooling, where a substantial loss of learning has occurred. If BHT disagreed with this analysis, during negotiations, they could provide evidence in the Anderlohr format to show different estimations. As noted before an analysis should be performed to determine an appropriate learning curve to use in the setback calculations.

3. Strengths and Weaknesses

a. Strengths

The strengths of the George Anderlohr method are:

1. The methodology could provide an excellent format from which to conduct negotiations concerning loss of learning calculations.
2. The calculations for the Anderlohr method are straightforward and relatively non-technical. This makes its use applicable to any loss of learning situation, from the most complicated to the routine.
3. The five elements of learning also provide an excellent framework from which to structure a Government negotiator's fact finding visit to a contractor's plant.
4. This method can be used to estimate the loss of learning due to a one-time break in production. In other words, historic data from other earlier breaks in production of the same product or a similar product are not required in order to use this method.

b. Weaknesses

The weaknesses of the George Anderlohr method are:

1. The method assumes that the learning curve slope after the break in production will be identical to the slope prior to the break. A negotiator could adapt this method to meet other circumstances by simply using a new learning curve slope once the setback point is determined.
2. This method assumes that the configuration of the product is the same after the break as it was before the break.

4. Factors Affecting Loss of Learning

The George Anderlohr method presents a straightforward, easy to use, methodology to determine the loss of learning due to a break in production. He notes five major elements to categorize loss of learning analysis and calculations. They are personnel learning, supervisory learning, continuity of productivity, methods, and special tooling. With this method, the first unit cost after a break in production may be calculated for any situation.

The major factor which this method fails to address is a methodology for determining the effect of loss of learning on the slope of the learning curve. For breaks of short duration it may be appropriate to use the same learning curve both before and after the break in production.

However, in a situation where a longer break in production occurs or when the procurement is a final buy-out, a separate analysis of the loss of learning effect on the slopes of learning curves may be necessary.

Another factor which surfaced during the analysis of these aircraft, which could have an impact on all factors, is the situation of a product phaseout/buy-out (the last buy or production run for a specified product). For both the C-2A and the AH-1W the planned acquisitions were to be the final lots produced. E.B. Cochran has determined that product phaseouts are typified by, "...parts shortages, cessation of progress, shrinking production rate and interruptions." [Ref. 20:p. 4-20] A factor for phaseout of a product should be included in the Anderlohr analysis to yield accurate estimates of loss of learning due to breaks in production.

E. DCAA METHOD

1. C-2A

The equation which forms the basis of this method is $Y = K(X - AZ)^c$. Step one in the DCAA method, as described in Chapter III, is to determine the learning curve slope (C value) for the peculiar labor hour data of Lot I, which occurred prior to the break in production. Using regression analysis, the researcher determined the slope to be 70.1% or a C value of -.51206.

Step two is to determine the value of K, the first unit cost. Again using regression analysis the value of K was calculated to be 341,704 hours.

Step three requires the calculation of the value of A, the number of units of production lost due to the break in production. Initially an R^2 value is calculated for the least square fit for the equation $Y = KX^c$, using the K = 341,704, C = -.51206, and A = 0 while letting X take on values 18 through 56, which represent post-break unit numbers 18 through 56. The calculated value for R^2 was 1.00. Next, a least squares fit for the equation $Y = K\,(X-AZ)^c$ was calculated using K = 341,704, C = -.51206, A = 1, Z = 1, N = 39, with X again being units 18 through 56. The R^2 value for this iteration was .999975. Since the R^2 value has decreased on this second iteration the process concludes and the value to use for A is zero. The value of unit one for Lot II can thus be calculated as follows:

$$Y = K\,(X-AZ)^c$$

$$Y = 341{,}704\,[18 - (0)(1)]^{-.51206}$$

$$Y = 77{,}781 \text{ labor hours}$$

This does not appear to be a good estimate. The estimate made by Grumman was 170% larger than this estimate using the DCAA method. Assuming that there is virtually no learning loss after a 17 year break in production is not valid and therefore, this method does not provide a reasonable estimate.

2. AH-1W

These calculations will be made using the total labor hours for the AH-1W. Using the same procedures as described for the C-2A, the learning curve slope for Lot II hours for the AH-1W was determined using regression analysis to be 97.1% with a corresponding C value of -.04241. The first unit cost of Lot II was calculated to be 7173 hours. The value of A=3 was determined to have the highest value for R^2. Thus the number of units determined to be lost due to the break in production was three. Substituting these calculated values into the DCAA equation yields the following estimate value for the first unit after the break in production:

$$Y = K\ (X-AZ)^{c}$$

$$Y = 7173\ [23 - (3)(1)]^{-.04241}$$

$$Y = 6317 \text{ labor hours}$$

If however, the labor hour data from Lot I is also included in the calculations, the learning curve slope would have been 78.2% and the first unit hours would have been estimated to be 20,560. Using these figures in the DCAA method, along with both Lot I and Lot II data yields an estimated value for A of zero. Therefore, the first unit after the break would have been estimated to be 5419 hours.

The two main reasons that this estimate, using both Lot I and Lot II, is smaller than the estimate using just Lot I is that the slope of the learning curve is steeper and that we are predicting a unit further out on the learning curve.

Both of these factors will tend to decrease the estimate of labor hours. Regardless of whether Lot I is included or not, the 6317 first unit labor hour prediction or the 5419 prediction seem too small when compared with the contractor's estimate of 17,820. The assumption of this model, that there is no significant learning loss during a break, doesn't seem to provide a reasonable estimate for this case with a 40 month break in production.

3. Strengths and Weaknesses

a. Strengths

The strengths of the DCAA method are:

1. It treats each lot as if it were a continuation of the last lot built, or in other words there is no learning lost during the break. When this assumption is met, this method provides good estimates of the hours for the first unit produced after a break. [Ref. 2]
2. It is a fairly easy method to use if a computer is available.

b. Weaknesses

The weaknesses of the DCAA method are:

1. It is an all or nothing method. It works well when all learning is assumed to have passed from lot to lot. However it does not allow for situations where there is a partial learning loss or a total learning loss during the break in production.

2. This method does not allow factoring in of other significant variables, which may effect the loss of learning, such as the partial loss of personnel, the production of a prototype or the change in the slope of the learning curve after the break in production.
3. This method does not provide a methodology to analyze a loss of learning situation. It strictly quantifies the loss of learning as factor of first unit costs and the slope of the learning curve. [Ref. 10]

4. Factors Affecting Loss of Learning

Since the DCAA equation is based on the original linear learning curve of T.P. Wright, the only values which will effect the first unit cost after a break are the slope (C value) and first unit cost (K value). Depending on the range of data used, values for the slope and first unit cost will be different. In the calculations performed for the C-2A and the AH-1W, all units of lots produced prior to the break in production were included in the regression analysis. Learning Curve theorists have often recommended that early units of a production lot and late units of production lot be excluded from calculations because they deviate from the true learning trend. These units are generally larger than the trend of the learning curve would predict. Including early and late units of production lots causes the prediction of the hours for the first unit to be larger than if they were excluded. Still others would try to alleviate any units which were subject to unusual deviations such as units produced during a strike.

This method assumes that learning is passed from one lot to the next. If this assumption proves true it can produce accurate results. [Ref. 20:p. 41] However, when losses of learning have taken place, no mechanisms or methodology are available to analyze the involved factors and then incorporate them into the model.

F. CUBIC CURVE METHOD ("S"-CURVE)

1. C-2A

The data needed to calculate the hours for units in a lot after a break in production using the cubic curve are the first unit and it´s production hours, (X_0 , Y_0), the last unit and it´s production hours, (X_n , Y_n), and the learning curve slope at these points. Use of the "S" curve has been found to provide good estimations for initial start-up production. [Ref. 22] Since the break-in production for the C-2A was almost 17 years, the new lot of 39 aircraft could be considered an initial production run.

The value for unit one, after the production break must first be estimated. As was seen in both the George Anderlohr and the DCAA approach, the first unit cost after a break was one of the critical factors which reflected the loss of learning due to a break in production. However, this method offers no specifics to use in calculating the first unit cost. This researcher performed a curvi-linear regression using the cubic curve for the pre-break data to estimate the first unit hours. The resulting value was 341,704 hours. This compares with a linear regression value of 371,125 hours. The last unit cost, 86,599 was calculated by projecting the original linear curve out to the 37th unit. The slope at the first point of production, after a break, will be assumed to be zero, due to the problems of starting up production after a 17 year break. The slope of the learning curve as it nears the final unit of production will be 80%, which was estimated by Grumman from historic data. The data to enter into the matrix manipulation is as follows:

$$(X_0 , Y_0) = (1 , 395{,}062)$$

$$(X_n , Y_n) = (39 , 86{,}599)$$

$$dx/dy_0 = 0$$

$$dx/dy_n = -.80$$

After using both matrix inversion and matrix multiplication, the values for the constants are calculated and the cubic curve equation is as follows:

$$Y = 11.24244 X^3 - 674.557 X^2 + 1315.387 X + 394409.9$$

The next step is to solve this equation for values one through 39 for X, to determine each units estimated labor hours. The resulting estimate of cumulative hours for the first ten units produced using the cubic curve, 4,132,966, is greater than the estimated total hours for the entire 39 units agreed upon between the Government and Grumman during negotiations, 2,996,707.

One other set of calculations was performed, for comparison purposes, using the cubic curve. The following data were used to determine the cubic curve equation:

$$(X_o \ , \ Y_o) = (\ 1,\ 341{,}704)$$

$$(X_n \ , \ Y_n) = (\ 39,\ 43{,}498)$$

$$dx/dy_o = 0$$

$$dx/dy_n = -.80$$

The data produced an estimate which after ten units, 3,262,481, was larger than the estimated total peculiar hours for the entire 39 units finalized during negotiations. This calculation indicates that by decreasing the value at unit one by 53,358 and by decreasing the value at unit 39 by 43,101 the cubic curve prediction for unit one through ten was reduced by 870,485. This highlights the fact that the value of the first and last unit hours will have a tremendous impact on cost estimates when using the cubic curve. Lowering the first and last unit hours will lower the overall predicted hours significantly. Using a linear learning curve with the same first unit hours and the same 80% slope would have resulted in an estimate of 1,542,793 for the first ten units. This indicates that a larger estimate will result from using the cubic equation versus the linear learning curve.

2. AH-1W

The first unit, 6971 hours, and the last unit, 6061 hours, for Lot III, were calculated by applying a non-linear regression analysis to labor hours per unit in Lot II. Once again an initial slope of zero at the first unit will be used to simulate the problems associated with initial start-up after a production break. The slope, as production nears the last unit will be -.971, which was the slope of the learning curve for Lot II production. The data to enter into the matrix manipulation is as follows:

$$(X_0 , Y_0) = (1 , 6971)$$

$$(X_n , Y_n) = (34 , 6061)$$

$$dx/dy_0 = 0$$

$$dx/dy_n = -.971$$

These values produced the following cubic equation:

$$Y = .049752 X^3 - 2.62672 X^2 + 5.104183 X + 6968.472$$

Using this equation, estimates for Lot III can now be made. The average hours for a Lot III unit using the cubic equation is 6518. This compares with a Lot II average of 6623 hours. It is very hard to judge whether or not this is a good estimate. While there is to be a 40 month break in production between Lot II and Lot III BHT will not lose all it´s learning since they will be performing upgrades on 21 AH-1T´s. However, the estimate of a first unit hours of 6971 may be too small in view of the length of the break and Lot III being the final production run of this helicopter.

Three other sets of calculations were done using the cubic curve. The first set of data was:

$$(X_0 , Y_0) = (1 , 6971)$$

$$(X_n , Y_n) = (34 , 6061)$$

$$dx/dy_o = 0$$

$$dx/dy_n = -.782$$

The second set of data was:

$$(X_o , Y_o) = (1 , 20560)$$

$$(X_n , Y_n) = (34 , 6061)$$

$$dx/dy_o = 0$$

$$dx/dy_n = -.782$$

The third set of data was :

$$(X_o , Y_o) = (1 , 20560)$$

$$(X_n , Y_n) = (34 , 6061)$$

$$dx/dy_o = -.90$$

$$dx/dy_n = -.782$$

The first set of data produced an estimate of 6517 for the average cost of a Lot III unit, the second set produced an estimate of 13,311 and the third set produced an average of 13,310. When analyzing the data it was apparent that changing the slopes has almost no effect on the average cost of a unit in a lot. The second set of data had a learning curve slope at the first point which was less than that used in the third set of data but the average cost per unit was almost identical, 13,311 to 13,310. The estimates produced by the second and third sets of data, used a first unit cost determined using regression analysis, including data from both Lots I and II. Including Lot I data, significantly increased estimates using the cubic curve for

Lot III, from 6518 to 13,311. The 13,311 figure would appear to be much too large since the aircraft is identical to that produced during Lot II, which had average unit hours of 6623.

3. Strengths and Weaknesses

a. Strengths

The strengths of the cubic curve method are:

1. When historic data indicate that the learning curve is most likely "S" shaped, then this model provides a mathematically sound means of estimating costs. [Ref. 22] [Ref. 23]
2. From the contractor´s perspective, the cubic curve provides a means to quantify non-linear learning curve data and capture the true cost in hours of production. Use of linear regression and linear learning curves would smooth out the aberrations of the "S" curve pattern of the data. The result, using linear learning curves would be a smaller estimate in hours than that produced using the cubic curve.
3. It allows quick calculations for various combinations of first unit, last unit, initial learning curve slope and final learning curve slopes. With a more accurate method of estimating these four factors, it could provide excellent estimations.

b. Weaknesses

The weaknesses of the Cubic Curve Method are as follows:

1. The cost analyst must estimate/calculate both the first unit cost and the learning curve slopes before using the cubic curve. These unit values could inadvertently serve as artificial constraints in terms of cost estimations. When using parametric cost estimating techniques, the accuracy of estimates is only as good as the data which are being used. This is true with the Cubic Curve method. The accuracy of the estimates for lots of production after a break, will only be as good as the estimates of the first unit cost and the slopes of the learning curves.
2. From the Government perspective, the cubic curve will lead to higher cost estimates than the log linear method.
3. The Cubic Curve is simply a parametric cost estimating method. Other methods must be used to determine the data which will form the shape of the "S" curve (learning curve slopes) parameters. Simply it does not provide a methodology to calculate the loss of learning. It assumes that each production lot will exhibit the symptoms of initial start-up as described in Chapter II.

4. Factors Affecting Loss of Learning

This method does not identify any unique factors which affect the loss of learning due to breaks in production. Its major assumption, that a break in production causes the next lot to simulate the "S"/cubic curve would indicate that the first unit of production after the break and the initial learning curve slope are the keys to measuring the actual loss of learning. However, this method offers no method for actually calculating these two values.

G. PINCHON AND RICHARDSON METHOD (PR)

1. C-2A

To use the PR method for the C-2A´s, it would have been necessary to calculate new constant values for A_0 , A_1 , and A_2 . This is because labor hours for the C-2A exceed the maximum value allowed by the PR equation of 50 hours. Unfortunately there were no previous breaks in production from which to gather data for a multiple regression analysis to calculate new values for the constants in the PR equation. Therefore, the PR method could not make estimates for the procurement of C-2A´s.

2. AH-1W

Since the PR method only yields reasonable estimates for items which require less than 50 labor hours of production, this researcher had to perform multiple regression calculations to determine new constants for their general equation. To do a multiple regression analysis of two independent variables, at least four historic observations were necessary. Final Assembly labor hours for four separate break in production occurrences which took place over the last 12 years were used as input for this multiple regression. The independent variables were X_1, the last unit labor hour for lots preceding the break, and X_2, the learning curve slope, while the dependent variable was Y in the following data:

observations	X_1	X_2	Y
1	555	.7716	1102
2	834	.9138	1903
3	1095	.7816	3592
4	1087	.9040	1851

The resulting regression equation, which had an R^2 of .78, was:

$$\ln Y = 5.681427 + .001774\ X_1 - 1.72745\ (\ \ln X_2\ )$$

From the actual labor hour data from the production of Lot II helicopters, the X_1 value was determined to be 2392.9. The X_2 value of .987 was calculated by applying a least squares fit to the Lot II data. Inserting these two values into the new equation yields an estimated value for the first unit labor hours of 20,931. This value for the first unit after a break in production does not appear to be realistic in view of the sample data which were used. It does appear that as with the original findings of Pinchon and Richardson, that this theory is only valid for predicting within close range of the values of the historic input data into the multiple regression. Since the X_1 value used for estimating

Lot III was 2392.9, as compared with sample data values of 555, 834, 1095, and 1087, the results seem to indicate that our X_1 value was too large to produce reasonable results using the PR method. A second calculation was performed using both Lot I and Lot II data and using unit 19, 2318 hours, as the last unit produced to eliminate the tail-up effect. The data produce an even larger estimate of 27,605. Again the data appear to be out of the range of predictive effectiveness for our calculated PR equation.

3. Strengths and Weaknesses

a. Strengths

The strengths of the PR method are as follows:

1. It provides good approximations for items which indicate a total loss of learning and which meet the less than 50 labor hours per unit criteria [Ref. 2].
2. It provides good approximations when the last unit before the break is within close range, in value to the sample data values.

b. Weaknesses

The weaknesses of the PR method are as follows:

1. It treats each lot as if it were new production. The PR method provides no means to factor in a partial loss of learning, such as might happen if only half of the work force was lost due to attrition during a break.

2. The method does not provide good estimates when the last unit produced prior to a break is not similar, in value to the sample data last units produced which are used to calculate the parameters for the model.
3. The parameters in this method must be recalculated whenever the range of sample data values change.
5. This model assumes that the learning curve is the same before and after the production break.
6. The model can not be used if there are no historic breaks in production from which to do a regression analysis.

4. Factors Affecting Loss of Learning

In developing their original equation PR found that "...a break of as much as 23 months was shown to be statistically insignificant in estimating the cost of a production lot following a break in production." [Ref. 12:p. 23] PR may have been able to eliminate the length of the production break with their sample data but it may not be indicative of other industries and other products. The PR method traces the loss of learning through the effect on historical labor hours and the estimated slope of the learning curve after the break. While this type of analysis may work within the extremely confined data sample from which PR chose, calculations for BHT are indicative of the restrictive nature of this approach.

H. SUMMARY

In this Chapter, the four methods used to calculate loss of learning were applied to the C-2A and AH-1W aircraft programs. An assessment of the strengths, weaknesses and factors effecting loss of learning for each was presented.

V. PRINCIPAL FINDINGS, CONCLUSIONS AND RECOMMENDATIONS

A. PRINCIPAL FINDINGS AND CONCLUSIONS

The objective of this study was to identify both the major factors which cause/influence the loss of learning due to breaks in production and methods available to quantify this loss of learning. The principal findings and conclusions are derived from personal interviews and the analysis of the Grumman C-2A and the BHT AH-1W, using the four methods the researcher found which measure the loss of learning due to breaks in production.

1. The parametric methods to calculate loss of learning, the Cubic Curve, the Pinchon and Richardson, and the DCAA method are all only as good as the input data to their models. Each method produced significantly different estimates depending on either the last unit hours prior to the break or the first unit hours after the break. These methods produce reasonable estimates when the circumstances of production prior to the break are relatively unchanged after the break. When there has been a significant change in circumstances, however, these methods produce unreliable estimates.

2. A major factor left out of all four methods for calculating learning loss during a break in production was motivation. An underlying assumption of learning curve

theory and these four methods is that workers and their company will be motivated to learn and, therefore, reduce cost over time, by reducing labor hours as units are produced. However, when the BHT case was analyzed, it was evident that a predicted learning curve slope for a future contract might be unrealistic since Lot III was a buyout/last production run for the AH-1W. The tail-up effect, which often occurs at the end of production runs, is a well documented phenomenon. It is entirely logical to assume that the tail-up effect, with all of it´s negative effects on learning, may well exist throughout the Lot III production of the AH-1W.

3. That the George Anderlohr Method provides the most versatile, easy to use method for identifying the factors which cause the loss of learning due to a break in production. The Anderlohr method provides a methodology to analyze a break in production of any length, for any product. It could also provide an excellent format from which to either, conduct a fact finding visit to a contractor´s plant or conduct negotiations concerning the effect on labor hours from a break in production. On the other hand, the three parametric methods provide a viable means to quantify the loss of learning in certain circumstances but they do not provide a means to analyze the factors which cause the loss of learning.

4. Separating aircraft into those components which are affected by a break in production and those which are not, resulted in a fair and reasonable estimate of labor hours by Grumman. This was an excellent method since it allowed the use of separate learning curves to analyze those components unique to the C-2A, therefore affected by the break, and those which were similar to the components in an aircraft in production during the break, the E-2C.

B. RECOMMENDATIONS

1. A learning curve slope adjustment clause should be used in contracts where their has been a break in production. The clause would be structured in a similar manner to an Economic Price Adjustment (EPA) clause. It would serve the purpose of reducing, to a significant extent, the risk of both the Government and the contractor for labor hour estimates in contracts for items subjected to a break in production.

2. For the two aircraft programs evaluated in this thesis, the George Anderlohr Method would have been the best method to calculate the loss of learning due to a break in production. The Anderlohr Method would have been equally effective for the C-2A, with a 17 year break, or the AH-1W, with a 40 month break, since it allows for the identification, evaluation, and subsequent quantification of those factors which may have been affected by a break. The three parametric methods, the DCAA, PR, and Cubic Curve do

not seem to provide reasonable estimates for the loss of learning in the two cases analyzed. These methods would not be recommended unless the specific break in production being analyzed can be shown to meet their rigid assumptions.

3. Pertinent DOD manuals and instructions should be modified to include the George Anderlohr Method for measuring the loss of learning due to a break in production. This method should provide assistance to cost analysts and negotiators for both large and small dollar value acquisitions which have been subject to breaks in production.

4. When parametric methods are used by the contractor to estimate either the first unit hours or the hours of a lot following a break in production, historical data, should be analyzed very carefully to determine it´s relevance since it is often produced under significantly different conditions than are present during the current proposed contract. A contractor´s proposal should also be analyzed to ensure that applicable learning curve theory was used correctly.

C. ANSWERS TO THE RESEARCH QUESTIONS

As a summary of the information presented in this thesis, the following is a restatement of the primary and subsidiary research questions and their answers.

Primary research question

Question: <u>What are the principal factors which contribute to a loss of learning due to production breaks and how might these factors be quantified for use during negotiations?</u>

Answer: The principal factors are personnel learning, supervisory learning, continuity of production, methods, special tooling, along with product phaseouts and a change in configuration of the product. The four methods found to quantify these factors were the George Anderlohr method, the DCAA method, the PR method, and the Cubic Curve method.

Subsidiary research questions

Question: <u>What methods have been and are used to measure loss of learning due to breaks in production?</u>

Answer: There were two methods found which measure the loss of learning due to a break in production. First, the George Anderlohr method, provides a means to analyze and then quantify the factors which are affected by a break in production. The second method, the parametric approach, estimates the loss of learning based on historical data accumulated prior to the break in production. Methods used by both Grumman and BHT, along with the DCAA, PR, and the Cubic Curve are parametric in nature.

Question: <u>What factors are affected by production breaks?</u>

Answer: The factors are personnel learning, supervisory learning, continuity of production, methods, and special tooling.

Question: <u>How can the effect on these factors be quantified and measured?</u>

Answer: The George Anderlohr approach was the only method found which provides a methodology to first measure and then quantify the effect of a break in production on these loss of learning factors.

Question: <u>How best can negotiators use quantitative models of loss of learning due to production breaks in the buying process?</u>

Answer: The best method for negotiators to use would be the Anderlohr approach. It is a logical, easy to use methodology which is appropriate for any type of break in production. If a parametric method must be used, then the negotiator should carefully analyze the available historical data to ensure that it meets the required assumptions of the method.

D. AREAS FOR FURTHER STUDY

The George Anderlohr method identifies five elements of learning which are affected by a break in production. A negotiator or cost analyst must analyze each of these elements/factors, to determine the magnitude of their learning loss. It is recommended that research be conducted to determine which factor/element of learning suffers the greatest loss due to a break in production. This research should focus on trying to develop correlations between groups or categories of similar weapon systems and the factor/element of learning most affected by the break in production. This information would identify for a negotiator the factors, for a given weapon system, which have historically proven to be the most important. The negotiator could then concentrate his analysis or fact finding on this factor. The negotiator could also use this information to weight the five elements of learning loss in the George Anderlohr method.

APPENDIX

CONTRACTOR DATA USED IN ANALYSIS

A. GRUMMAN DATA

Unit	Labor Hours
4.5	158,886
10.0	103,936
17.0	80,626

B. BHT DATA

Unit	Labor Hours
23	6810.7
24	7042.5
25	6966.3
26	6540.3
27	6639.1
28	6819.0
29	6436.9
30	6751.2
31	6764.7
32	6929.9
33	6389.9
34	6568.7
35	6643.8
36	6657.1
37	6569.1
38	6670.4
39	6405.8
40	6587.2
41	6129.3
42	6146.9
43	5786.0
44	5675.1

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